2000-09

# High frequency sonar components of normal and hearing impaired dolphins.

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http://hdl.handle.net/10945/7708

# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

# THESIS

**HIGH FREQUENCY SONAR COMPONENTS OF NORMAL AND HEARING IMPAIRED DOLPHINS**

by

David C. Dye

September 2000

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Co-Advisor: Ching-Sang Chiu

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| REPORT DOCUMENTATION PAGE | *Form Approved OMB No. 0704-0188* |
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| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE<br>September 2000 | 3. REPORT TYPE AND DATES COVERED<br>Master's Thesis |
|---|---|---|

| 4. TITLE AND SUBTITLE: Title (Mix case letters)<br>High Frequency Sonar Components of Normal and Hearing Impaired Dolphins | 5. FUNDING NUMBERS |
|---|---|
| 6. AUTHOR(S) Dye, David C. | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Naval Postgraduate School<br>Monterey, CA 93943-5000 | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>Office of Naval Research, Code 322W | 10. SPONSORING / MONITORING AGENCY REPORT NUMBER |

**11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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**13. ABSTRACT** ***(maximum 200 words)***

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Data from three different toothed whales, a normal Bottlenose Dolphin, a Bottlenose Dolphin with a hearing impairment and a Beluga Whale, was analyzed. It was observed that the animals reduced the interval between clicks when they located a target. Correlating the signal data to the video data made this observation possible. It appeared the animals searched with widely spaced clicks, then narrowed the click period upon target detection. Also, it was noted that the frequency of isolated clicks decreased as click period decreased. However, the hearing impaired Dolphin maintained his click frequency regardless of click periodicity.


| 14. SUBJECT TERMS<br>Marine Mammal Systems, Bio-SONAR, Mine Detection, Dolphin SONAR, Echolocation Signals | | | 15. NUMBER OF PAGES 88 |
|---|---|---|---|
| | | | 16. PRICE CODE |
| 17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT<br>UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
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# HIGH FREQUENCY SONAR COMPONENTS OF NORMAL AND HEARING IMPAIRED DOLPHINS

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Lieutenant, United States Navy
B.S., Jacksonville University, 1994

Submitted in partial fulfillment of the requirements for the degree of

**MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY**

from the

**NAVAL POSTGRADUATE SCHOOL**
**September 2000**

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## ACKNOWLEDGEMENTS

I would like to thank the many people who have lent their encouragement and support over the period of this research. Additionally I wish to acknowledge the financial support from Office of Naval Research Code-322W, Dr. Douglas Todoroff, Program Manager.

My advisor, Professor Thomas Muir, has spent countless hours lecturing, computing and designing to aid me in this pursuit. His counsel has been paramount in completing this work.

I also wish to thank my co-advisor, Professor C.S. Chiu, for his patience and guidance throughout this research.

This research owes much to the community of marine biologists. Much thanks goes to Dr. Sam Ridgway of the Space and Naval Warfare Systems Center in San Diego, for providing me the opportunity to work with "Buster" and "Nino," Bottlenose Dolphins and "Muk-Tuk," a Beluga Whale. An additional thanks goes to the trainers that assisted in the data collection and determined the dolphin's behavior. Specifically, Patricia Kamolnick, Steve Meck, Natalie Hall, Jamie Atler and Dru Clark.

Finally, I wish to thank my beautiful wife Brenda and daughter Sierra, who have shared with me both the frustrations and triumphs of this research. Thank you for persevering with my absence and long hours required to complete this thesis.

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This work is solely dedicated to my father,

James H. Dye

You will always be my guide.

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# I. INTRODUCTION

The work described in this thesis is a continuing research effort begun by the Applied Research Laboratories of the University of Texas at Austin (ARL-UT), and sponsored by Code 322W at the Office of Naval Research (ONR). This work was accomplished in collaboration with Space and Naval Warfare Systems Center (SSC) San Diego, and has recently involved thesis research at the Naval Postgraduate School. Previous research has identified high frequency components of Dolphin sonar that were unknown until then. The primary focus of present research is to further examine the Dolphin sonar by comparing separate animals of the same species and a different species. This investigation into Dolphin sonar will hopefully continue to unlock the secrets of these signal-processing animals.

## A. BACKGROUND

Dolphin sonar experiments in the last 40 years have used receive transducers that are limited to approximately 130 kHz and lower. Recent experiments since 1997 by US Navy Lieutenant Ronald Toland, Ms. Diane Blackwood of Texas A&M, Dr. Thomas Muir of the Naval Postgraduate School and Dr. Sam Ridgway of SSC San Diego have demonstrated that Dolphin sonar signals extend up to 500 kHz. This experiment will in part continue the work of LT Toland, and will be expanded to

explore new signal characteristics under different operating conditions.

Prior research on the bottlenose dolphin species has indicated a high-resolution capability of marine bio-sonar to classify and distinguish between small man made targets, as well as structural features within them. This reported level of resolution can not be achieved with man made sonars operating in the Dolphin sonar frequency range (approximately 100kHz), with pulse lengths as previously published. [Ref. 1] Cetacean sonar performance reported in the literature has sometimes seemed to contradict the uncertainty principle, a rule of physics, as interpreted for acoustics. For sonar, this principle has at least two corollaries.

First, for pulse envelope detection in the time domain (i.e. pressure amplitude of a packet of individual oscillations), the finest range resolution that is processed is equal to half the pulse length multiplied by the sound speed. A sonar pinging at two closely spaced target components will begin to experience a null between the two pulses returning to the field of view. For example, a sonar signal envelope with a four cycle transmission centered at 100kHz in 1500 m/sec speed water, would have a range resolution of (4 X (1.5x10^5)/10^5)/2 = 3cm.

Second, for interferometric detection (i.e. the comparison of individual wave fringes within a packet), the finest resolution is approximately one quarter of a

wavelength of the sound being processed. A Dolphin using a click centered at 100kHz would have a nominal single click period of 1/10^5 sec, with a wavelength of 1.5x10^5/10^5 cm, and a quarter wavelength fringe resolution of about 0.4 cm.

Previously reported bio-sonar experiments on dolphins have shown they are capable of achieving much higher resolution. The capability of a bottlenose dolphin to discriminate differences in the wall thickness of hollow steel cylinders has been studied by many authors, including Titov [Ref. 2]. His animal was able to react to a wall thickness difference of 0.2 mm with a 75% correct response level. The discovery of the existence of high frequency signal components (greater than 100-150 kHz) may help to explain why a dolphin achieves a much higher resolution than permitted by this rule of physics. [Ref. 3]

The Dolphin's ability to recognize and classify targets buried in the sediments, in reverberation limited environments, is better than any man-made mine-hunting sonar system. In fact, marine mammals, although cumbersome, and expensive, are currently the only means the Navy has for detecting buried mines [Ref. 4]. Therefore, a brief description of the current U.S. Navy Marine Mammal Program is given in section C of this chapter.

## B. RESEARCH MOTIVATION AND OBJECTIVES

This thesis describes the results of an investigation into similarities and differences of sonar data from three toothed whales, and theories that result. This research has significance to both military and scientific applications. Specifically, a greater understanding of marine mammal sonar could aid in the development of better U.S. Navy sonar systems for detection and classification of sea mines that have been buried by sediments. This knowledge would also greatly improve the biological and physical modeling of animal acoustic systems.

## C. U.S. NAVY MARINE MAMMAL PROGRAM

The U.S. Navy's Marine Mammal Program incorporates specially trained Atlantic and Pacific bottlenose dolphins, white whales, and sea lions for mine detection and neutralization, swimmer defense, and recovery of exercise mines and torpedoes; though one animal species does not perform all listed tasks. Taking advantage of years of evolution that have produced animals well suited for these tasks, the Navy has evolved complex and sophisticated training techniques that enable these animals to conduct real-world operations. [Ref. 4]

The Marine Mammal Program began in 1960, when several Dolphins were used in hydrodynamic studies addressing

underwater torpedo design. In 1963, the Navy began studying the animals' deep diving and echolocation capabilities, and determined that Dolphins could work untethered in the open ocean. In the late 1960's the Navy developed a Dolphin swimmer detection and marking system under the code name Short Time. It deployed to Cam Rahn Bay, Vietnam in 1970, to guard an ammunition pier that had been the target of attacks by the Vietcong. Once the Dolphins were on scene and patrolling for infiltrators, the raids ended abruptly. In 1987, six Pacific Bottlenose Dolphins provided underwater surveillance and detection capability to support bases in the Persian Gulf. [Ref. 4]

Each operational Naval Marine Mammal System includes four to eight animal units which can be easily deployed on very short notice by strategic airlift to any part of the world, and can be worked from ships in forward areas. The system is divided into four programs utilized by the fleet, three of which include Bottlenose Dolphins:

•Mk 4 Mod-O - Pacific bottlenose dolphins detect mines and attach neutralization charges on the mooring cables of tethered mines moored near the bottom. The Navy is expanding this system's capability to neutralize all tethered buoyant mines.

•Mk 6 Mod-1 - Dolphins provide defense for harbors, ship anchorages and individual ships from infiltration by swimmers and divers. The Mk 6 elements participate

regularly in fleet exercises and real-world base security operations, providing a comprehensive surface and subsurface swimmer detection system.

•Mk 7 Mod-1 - Dolphins detect, locate, and mark or neutralize bottom mines and buried mines. This animal system represents the only operational buried-mine detection and neutralization capability in the world today.

The Mk4 and Mk7 Marine Mammal System detachments are integral operational elements of the Navy's mine countermeasures forces and have demonstrated the capability to operate for extended periods from forward-deployed ships. [Ref. 4]

There is also an additional system under development; the Experimental-8 Marine Mammal System will employ six dolphins for exploration and reconnaissance of in-volume, moored and bottom mine-like contacts in the Very Shallow Water Zone (10-40 feet depth). The Ex-8 dolphins will be deployable from an Amphibious Task Force ship for low-visibility, minefield exploration and reconnaissance. [Ref. 5]

The dolphins in the Marine Mammal Program satisfy critical requirements and real world operational needs that currently cannot be met as effectively or efficiently by any other means.

## D. THESIS OUTLINE

The second chapter provides a description of the dolphin echolocation system and characteristics of bio-sonar signals recorded with two wide band hydrophones. The third chapter describes the experiment involving three marine mammals and signals from various trials. The fourth chapter illustrates both raw and processed data from the experiment, with focus placed upon signal comparisons and differentiations. The fifth and final chapter describes conclusions, error sources and directions for further research.

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## II. DOLPHIN ECHOLOCATION SYSTEM

### A. DESCRIPTION

Dolphins echolocate by projecting a time series of pulses into the surrounding seawater and listening to the return signals reflected off of nearby objects. The Dolphin sound receptors and brain automatically process the return signals and likely generate a mental image for the Dolphin. Dr. Sam Ridgway, the Chief Veterinarian at SSC San Diego Marine Mammal Facility proposed that the nasal plugs create the signals. [Ref. 6] High frequency sound is produced when air travels back and forth between the plugs and the nasal wall. Once the clicks are generated, the sound waves are focused into a narrow beam by the "melon" in the Dolphin's forehead. This is the generally accepted description of Dolphin sonar transmission.

There have been discussions in the field of bio-sonar over exactly how a Dolphin receives its signal. Many scientists hypothesize that the Dolphin receives the return signals through nerves along the lower jaw, proven by Randall Brill. [Ref. 7] Dolphins, using their sonar, can tell the difference between small and large shapes, work in water too cloudy for light to pervade, penetrate thin layers of sediment and discriminate between multiple compositions in an object such as metal, wood, plastic, air or rock.

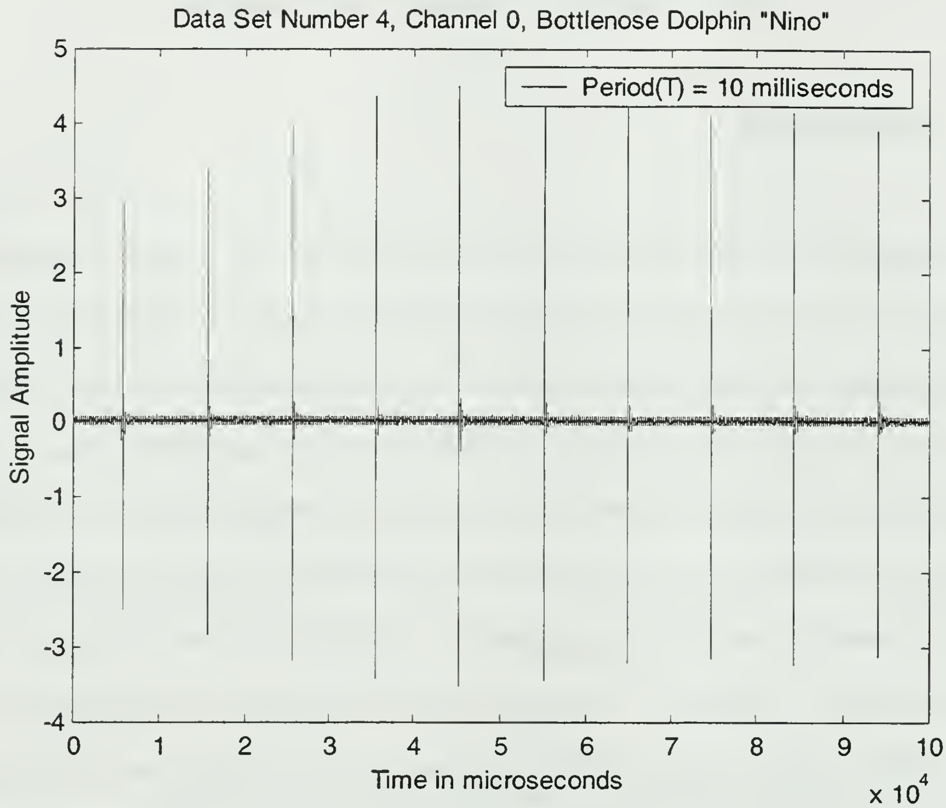


**Figure 1.** Successive Dolphin sonar Clicks

Dolphins make at least two distinct types of acoustic signals, one for echolocation and the other for communication. The communication signals are much lower frequency than echolocation signals, and can easily be discerned. Only echolocation signals are presented in this work. Figure 1 illustrates the time series transmissions, taken from this experiment, found in Dolphins during echolocation. In this figure, ten clicks are represented and this entire series of clicks occurred over a period of 100 milliseconds or one tenth of a second. Figure 2 illustrates a single echolocation click in greater detail.

This plot shows a single click that occurred over a period of 300 microseconds.

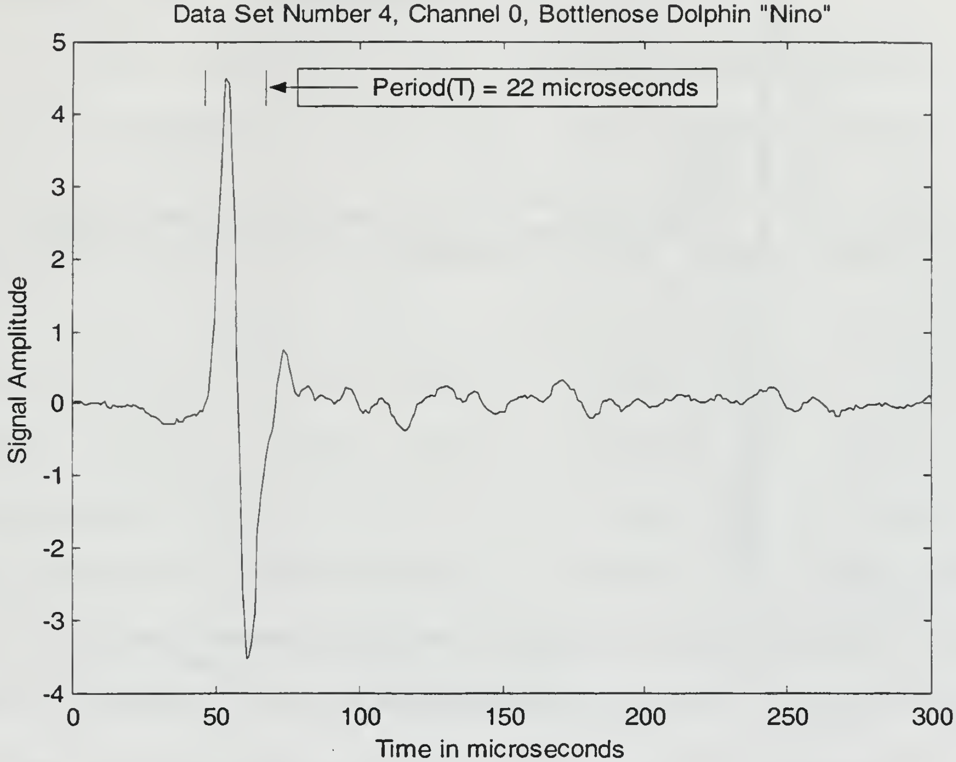


**Figure 2.** Single Dolpin sonar Click

The actual "click" is the single large waveform on the left side of figure 2. The signal structure that continues to the right of the click has been postulated to be reverberant reflections the Dolphin head. [Ref. 8] It is proposed that as the click passes through the melon, cranium and skeleton, portions of it make reflections before entering the water, allowing them to be received later than the original click. [Ref. 1] Figure 3 is a plot of five successive clicks and the accompanying reverberant data.

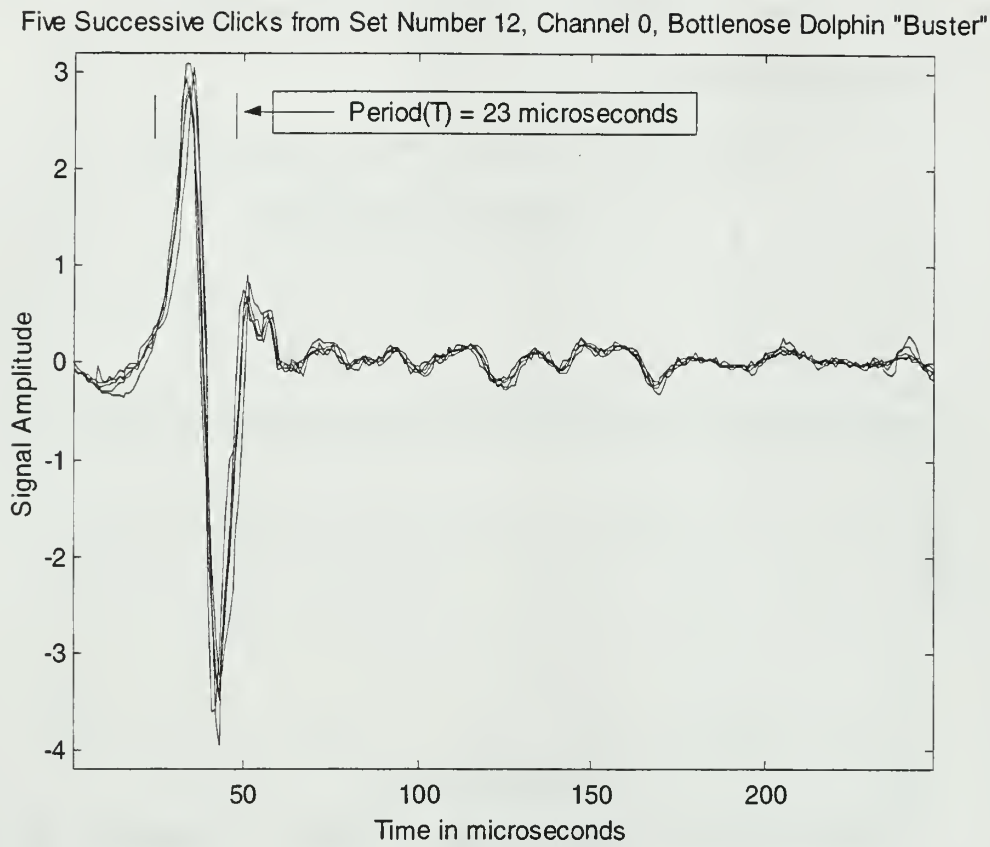


**Figure 3.** Overlay of Five Successive Clicks

## B. PERTINENT RESEARCH PRIOR TO 1997

It is well known that Dolphins are capable of producing extremely short duration, broad bandwidth, acoustic signals, which are utilized for echolocation. The ability of dolphins to accurately perceive their environment and to perform difficult recognition and discrimination tasks depends on the characteristics of these bio-sonar signals and how they are emitted, and processed upon reception. Signal characteristics and projection patterns have been

recorded and studied over a long period of time by many investigators, but operational mechanisms of Dolphin sonar yet remain to be delineated.

In 1973, Evans [Ref. 9] conducted sonar experiments on Dolphins in tanks. At that time, the frequency spectrum was believed to be in the vicinity of 30 to 60 kHz. The peak frequency (frequency of maximum energy) determined by Evans was 52 kHz. Then in 1974, Au observed significant energy, up to the limit of his detection system (130kHz), within a dolphin click. This energy extended to much higher frequencies than were previously measured. He conducted target detection experiments in Kaneohe Bay, Oahu, Hawaii, which involved measuring two bottlenose dolphin echolocation signals in open waters. His results showed that the signals had peak frequencies between 120 and 130 kHz, which were over an octave higher than the peak frequencies recorded by Evans. [Ref. 10]

Mitson [Ref. 11] published evidence of high-frequency acoustic emissions from a school of white beaked dolphin (*lagenorhynchus albirostris*) in the North Sea in 1987. While onboard a British fisheries research vessel, they just happened to record some fortuitous dolphin signals. These signals were detected by a sector side-scanning sonar of high bearing and time resolution, used as a passive listening device. The acoustic emissions from the dolphins had significant energy at frequencies around 305 kHz.

Again, this was about one octave higher than previously observed. [Ref. 11]

## C. RECENT DOLPHIN SONAR EXPERIMENTS

The hydrophone frequency response of the prior independent measurements of Evans, Au, and Mitson never extended high enough to conclusively capture all of the high frequency components. The high-resolution capability of cetacean sonars prompted ARL-UT to conduct further research into the existence of higher frequencies that may have been overlooked in prior research. The "Uncertainty Principle" hypothesis was proposed to the Office of Naval Research, who then funded its testing by the scientific method. The two species of dolphins recorded in San Diego Bay in 1997 by Muir, Blackwood, and Wilson, in collaboration with Ellsberry and Ridgway, were found to emit significant high frequency signal components extending to as high as 400 to 500 kHz. [Ref. 1] These signals were recorded using a hydrophone capable of measuring bio-sonar signals up to 2 MHz. Details of the hydroplane, experimental configuration, procedures, data processing and results can be found in Ref. 12.

# III. PRESENT BOTTLENOSE DOLPHIN ECHOLOCATION EXPERIMENT

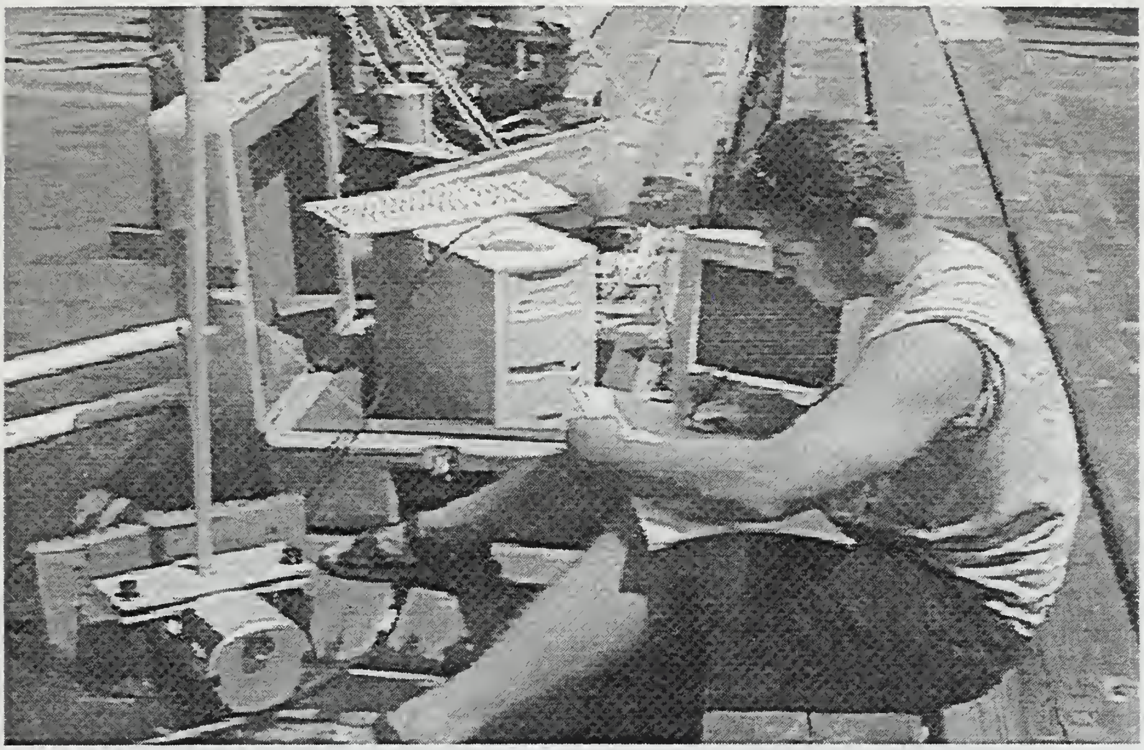

**Figure 4.** LT David Dye and the Experiment Aparatus

In this chapter will be discussed the configuration, procedure and results of the bottlenose dolphin echolocation measurements performed in July-August 2000 at SSC San Diego. The experiment involved two wide-band hydrophones mounted in a section of Sound Absorbing (SOAB) material [Ref. 12], along with a digital video camera to determine dolphin position. The general purpose was to study Dolphin signal production, while examining its relation to head orientation and both signal time and frequency content. Two Bottlenose Dolphins (*sp. Tursiops truncatus*) and a Beluga whale (*sp. Delphinapterus leucas*) were used. One of the Bottlenose

Dolphins has a hearing impairment (high frequency roll-off at approximately 30kHz) and it was desired to study the high frequency content of its sonar transmission.

## A. CONFIGURATION

The experimental assembly consisted of a sonar receiver array mounted on a submersible digital video camera housing, amplifiers, and a computer system to record the data. The sonar array consisted of two ITC-1089D transducers made by International Transducer Corporation, with a useful frequency response from 1000Hz to 400kHz. Calibration curves may be found in Appendix A. The digital video camera was a Sony model DCR-TRV900 (fig. 4), mounted in an Industrial Light & Motion submersible camera housing and attached to an eight hundred and sixty-one square centimeter (21cm X 41cm) section of SOAB material. SOAB (sound absorber) is a butyl rubber compound formerly made by the B.F. Goodrich Company to reduce high frequency acoustic reflections underwater. The two hydrophones were placed to the left and right of the camera lens, separated by 30cm. It had been noted that the Dolphins had a tendency to search in a left-right fashion, so both transducers were mounted in a horizontal plane. The two transducer cables were each attached to a separate SRS-560 preamplifier, made by Stanford Research Systems. The raw signals were band passed from 10kHz to 300kHz, then amplified with various gain

multipliers, ranging from 50 to 200. The filter had attenuation slopes of only 6dB per octave, thereby allowing for reception and use of signals considerably above and below the indicated filter settings. The filter was used to aid in reducing the reception of low frequency acoustic noise in San Diego Bay and high radio frequency noise from other sources.

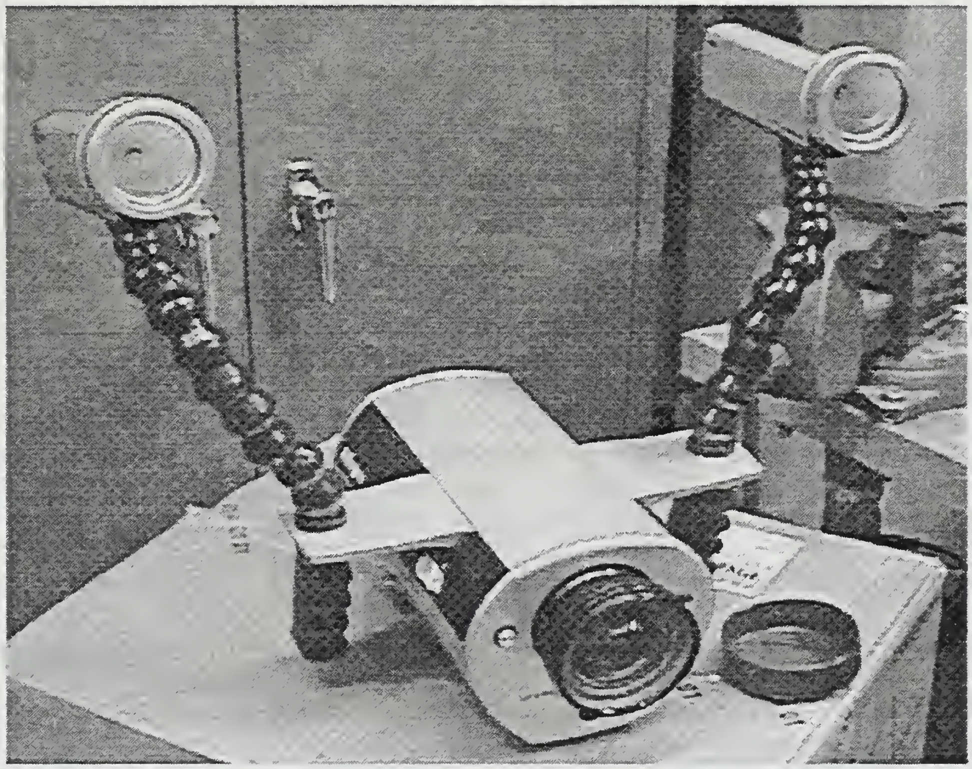

**Figure 5.** Underwater Camera Housing

The signals were received at a National instruments terminal box, BNC-2010 and fed into a PCI data acquisition card mounted inside a personal computer. The card was a National Instruments PCI-6110E DAQ unit that had a maximum sampling rate of 5 Ms/s (million samples per second) and a

capacity of eight channels of analog input. For this experiment, two channels were utilized at a sampling rate of 1 Ms/s. Data samples five seconds in duration were recorded directly to the data acquisition card and transferred to the computer hard drive.

## B. PROCEDURE

The camera housing/transducer array assembly was suspended within one of the Dolphin pens at SSC San Diego. Recordings were made with and without a 10cm steel sphere in front of the lens, either above or below the field of view, at a range of 35cm. The following table illustrates the trials and configurations used.

Data was recorded on three different animals with the names and Navy identification numbers, "Nino" (TT646M), "Buster" (TT727M) and "Muk-Tuk" (DL574F). Both Buster and Nino are Bottlenose Dolphins (*sp. Tursiops truncatus*) while Muk-Tuk is a Beluga whale (*sp. Delphinapterus leucas*). Due to the immense volume of data recorded, all data presented in this work is limited to data set number 5 from "Nino," data set 1 from "Buster" and data set 5 from "Muk-Tuk."

| Dolphin | Data Set | Target | Gain |
|---|---|---|---|
| Muk-Tuk | 1 | none | 500 |
| Muk-Tuk | 2 | below lens | 500 |
| Muk-Tuk | 3 | above lens | 500 |
| Muk-Tuk | 4 | none | 500 |
| Muk-Tuk | 5 | above lens | 100 |
| Muk-Tuk | 6 | above lens | 100 |
| Muk-Tuk | 7 | below lens | 50 |
| Muk-Tuk | 8 | none | 50 |
| Muk-Tuk | 9 | below lens | 50 |
| Muk-Tuk | 10 | none | 50 |
| Muk-Tuk | 11 | in front of lens | 50 |
| Muk-Tuk | 12 | none | 50 |
| Muk-Tuk | 13 | in front of lens | 50 |
| Muk-Tuk | 14 | above lens | 50 |
| Muk-Tuk | 15 | none | 50 |
| Muk-Tuk | 16 | above lens | 50 |
| Muk-Tuk | 17 | below lens | 50 |
| Muk-Tuk | 18 | none | 50 |

| Dolphin | Data Set | Target | Gain |
|---|---|---|---|
| Nino | 1 | in front of lens | 50 |
| Nino | 2 | below lens | 50 |
| Nino | 3 | none | 50 |
| Nino | 4 | none | 200 |
| Nino | 5 | above lens | 200 |
| Nino | 6 | none | 200 |
| Nino | 7 | in front of lens | 200 |
| Nino | 8 | none | 200 |
| Nino | 9 | none | 200 |
| Nino | 10 | below lens | 200 |
| Nino | 11 | none | 200 |
| Buster | 1 | in front of lens | 100 |
| Buster | 2 | above lens | 100 |
| Buster | 3 | below lens | 100 |
| Buster | 4 | in front of lens | 100 |
| Buster | 5 | above lens | 100 |
| Buster | 6 | in front of lens | 100 |
| Buster | 7 | none | 100 |
| Buster | 8 | none | 100 |
| Buster | 9 | in front of lens | 100 |
| Buster | 10 | none | 100 |
| Buster | 11 | below lens | 100 |
| Buster | 12 | none | 200 |
| Buster | 13 | none | 200 |
| Buster | 14 | none | 200 |

**Table 1.** Recording Session Data

## C. RESULTS

### 1. Raw Data

#### a. *Bottlenose Dolphin with Normal Hearing*

The following data, from the Dolphin "Nino," is considered the baseline for this experiment, since it will be compared to a hearing impaired Bottlenose Dolphin and a

Beluga Whale. Data set number 5 displayed some very interesting time series structure, as illustrated in figure 6. By analyzing the video that was recorded at the time of this data sample, the Dolphin appeared to locate the target at the time the click period decreased. "Nino" changed click period from 37 milliseconds to 11.5 milliseconds over a time span of 500 milliseconds, or one-half of one second. While this data set was not necessarily representative of the limit of "Nino's" abilities, it contained his greatest change in click period and his smallest click period of any of his data sets. In contrast, this data set had the smallest change in click period of the three animals from which data was collected.

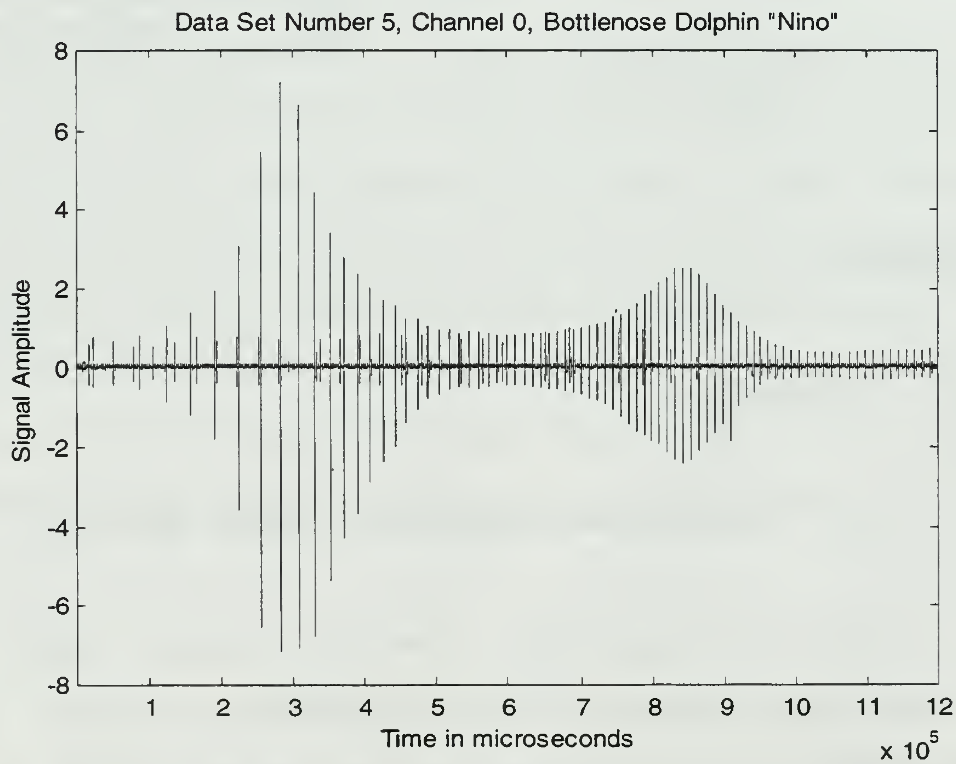


**Figure 6.** Time Series Data from Dolphin "Nino"

### *b. Bottlenose Dolphin with Impaired Hearing*

The phenomenon of decreasing click period was also observed in the Dolphin "Buster" as he appeared to locate the target. However, this Dolphin performed a much greater change in click period over the same length of time. "Buster" changed his period between clicks from 22 milliseconds to 2.2 milliseconds over a time span of 60 milliseconds. While the amplitude of the normal Dolphin's sonar clicks was much higher in these two examples, "Buster" displayed equivalent amplitude in other data sets, though not with the same small click period. Even so, the small click period displayed by the hearing impaired Dolphin suggests that he has the ability and intent to gather more acoustic information about his surroundings over a given length of time. Figure 7 illustrates the time series plot of the Dolphin sonar transmission from "Buster."

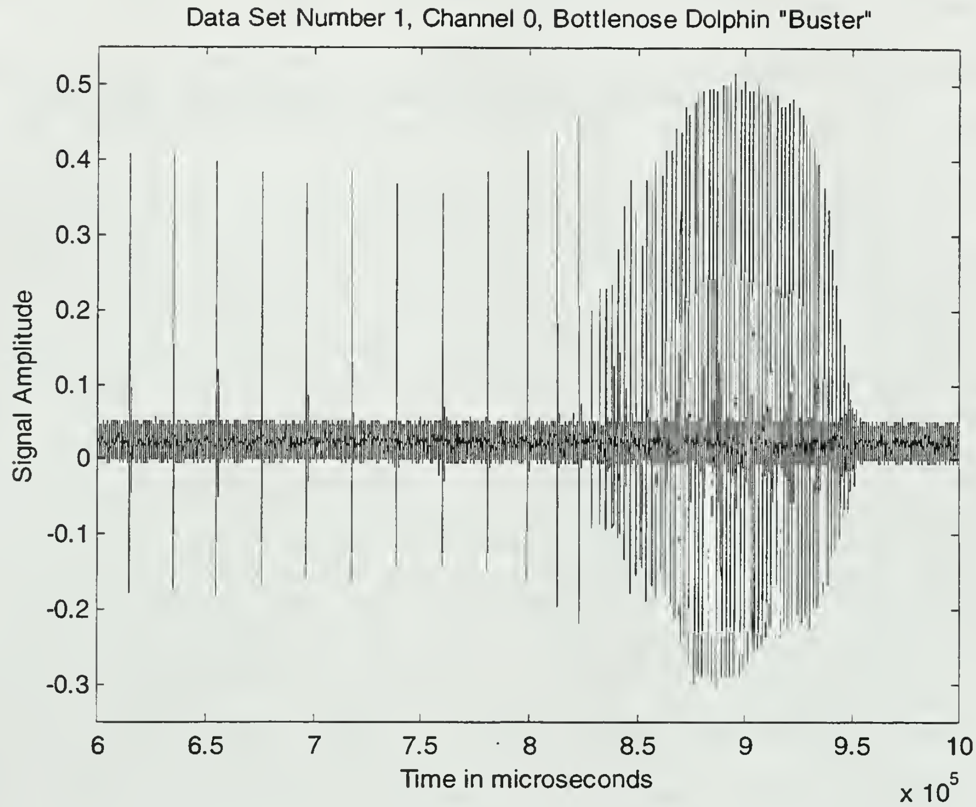


**Figure 7.** Time Series Data from Dolphin "Buster."

### c. *Beluga Whale, "Muk-Tuk"*

Similar changes in click period were observed in the Beluga whale named "Muk-Tuk." Figure 8 illustrates a portion of one of the time series data sets recorded from the Beluga Whale. "Muk-Tuk" also displayed the ability to vary click period. Examination of video data revealed an apparent location of the target at the time the click period was dramatically decreased. (Fig. 8)

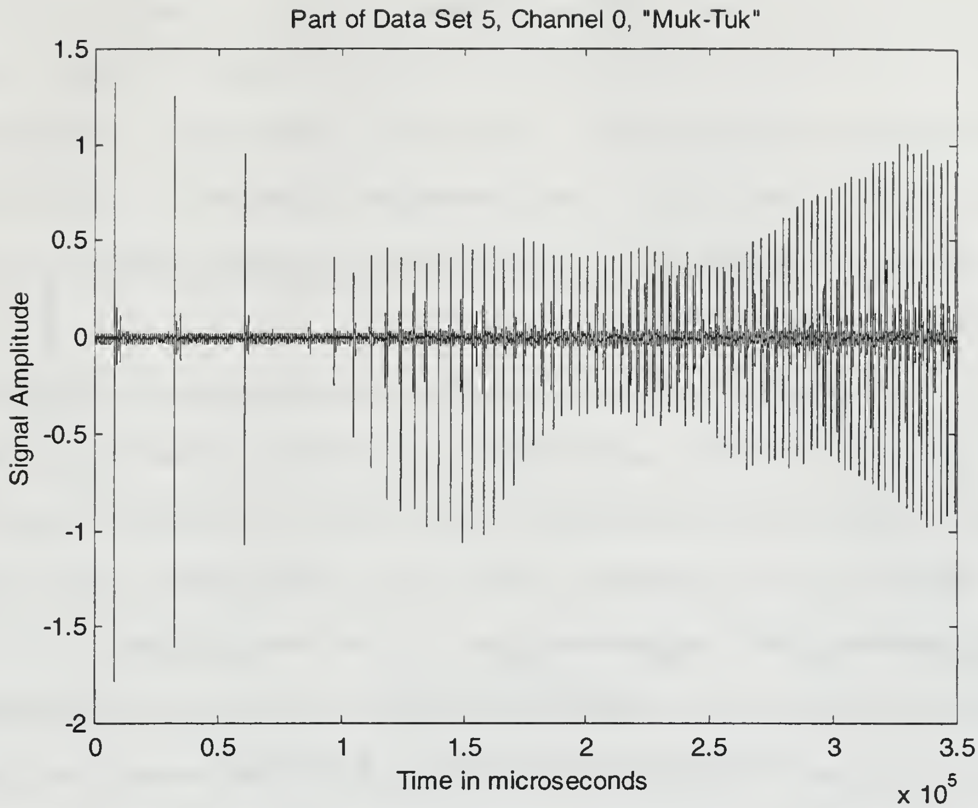


**Figure 8.** Time Series Plot of Beluga Whale "Muk-Tuk."

### 2. Fast Fourier Transformed (FFT) Data

#### *a. Introduction*

As previously stated, data processing was performed in MATLAB using the Signal Processing Toolbox. Fast Fourier Transforms (FFT) were run on the three different sets of the same collected data: individual clicks, clicks with reverberation and noise between clicks. Isolated clicks were computed directly by the MATLAB FFT function; however, both single clicks with reverberation and

noise were processed then averaged to gain a more accurate picture of the true spectra. All single clicks with reverberation were split into 30 continuous segments, processed with an FFT, then averaged together. Noise was split into 40 segments, and the same process applied. All FFT's were computed in 1Hz bins.

A plot of an individual click appears in figure 9. Noise exists at a low amplitude and is displayed to the left of the large amplitude spike, while the reverberant data is the signal that appears after an individual click for approximately 400 microseconds. It is unknown if the Dolphins utilize the reflected energy from the reverberant portion of their transmission; however, some waveforms show a great deal of structure, demonstrating the possibility the reverberant data is being used. There is a contradiction between the maximum resolution of a Dolphin's sonar and the Dolphin's ability to discriminate between very small objects. Using a lower frequency click, the resolution is impossible under the current uncertainty principle. It is proposed that the Dolphins either use their sonar in ways that violate the uncertainty principle, or they use the reverberant portion of their sonar transmission to attain the higher resolution. In light of this observation, scientific evidence proves otherwise. [Ref. 1] Figure 10 more closely illustrates the click and reverberant data structure, on an expanded time scale.

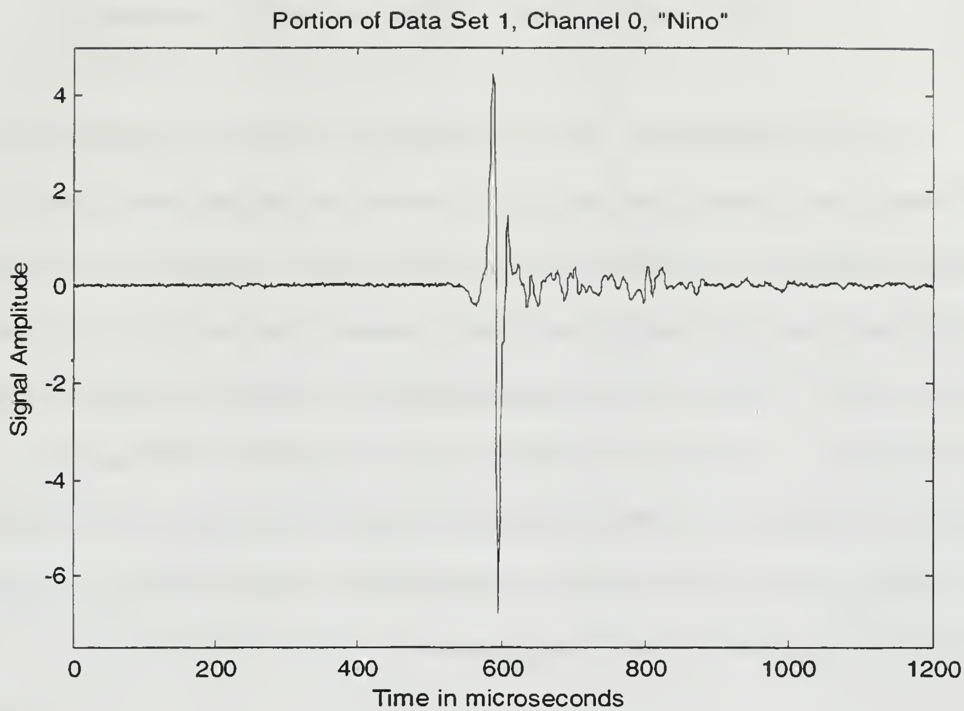


**Figure 9.** Isolated Sonar Click

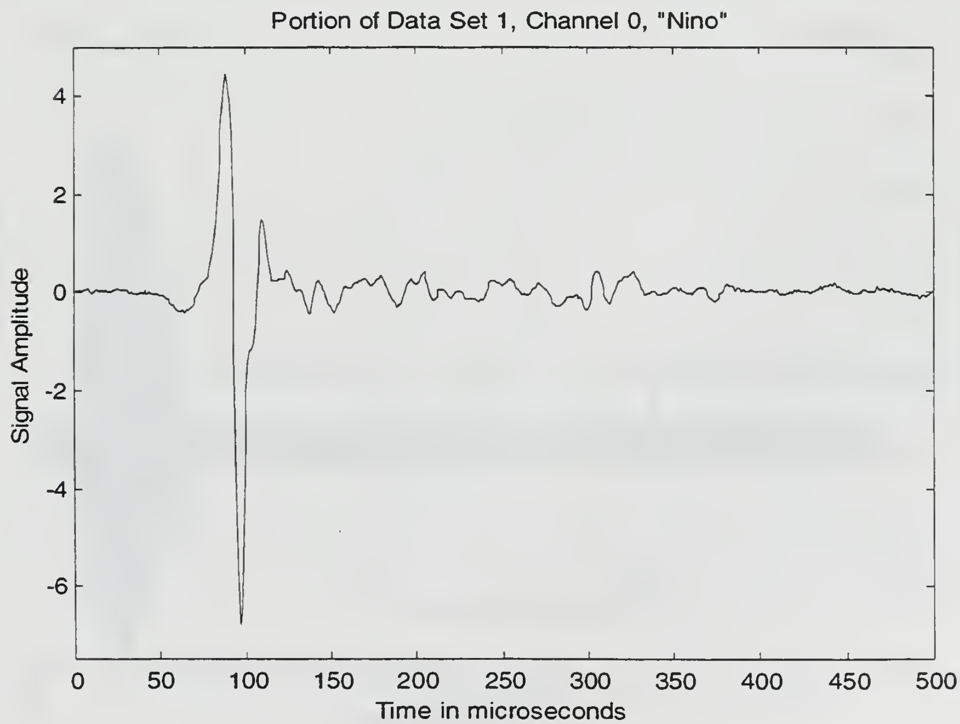


**Figure 10.** Click with Reverberant Data.

### b. *Processed data from Dolphin "Buster"*

The MATLAB FFT program was applied to two different data lengths to gain a better understanding of the Dolphin signals. All three Dolphin's clicks were plotted against noise in their frequency spectra, and both Dolphins' clicks with their reverberant data were plotted against noise, also in their frequency spectra. Finally, both Dolphins' signals were compared with their own click against their own click with their reverberant data. The following figures illustrate the FFT plots.

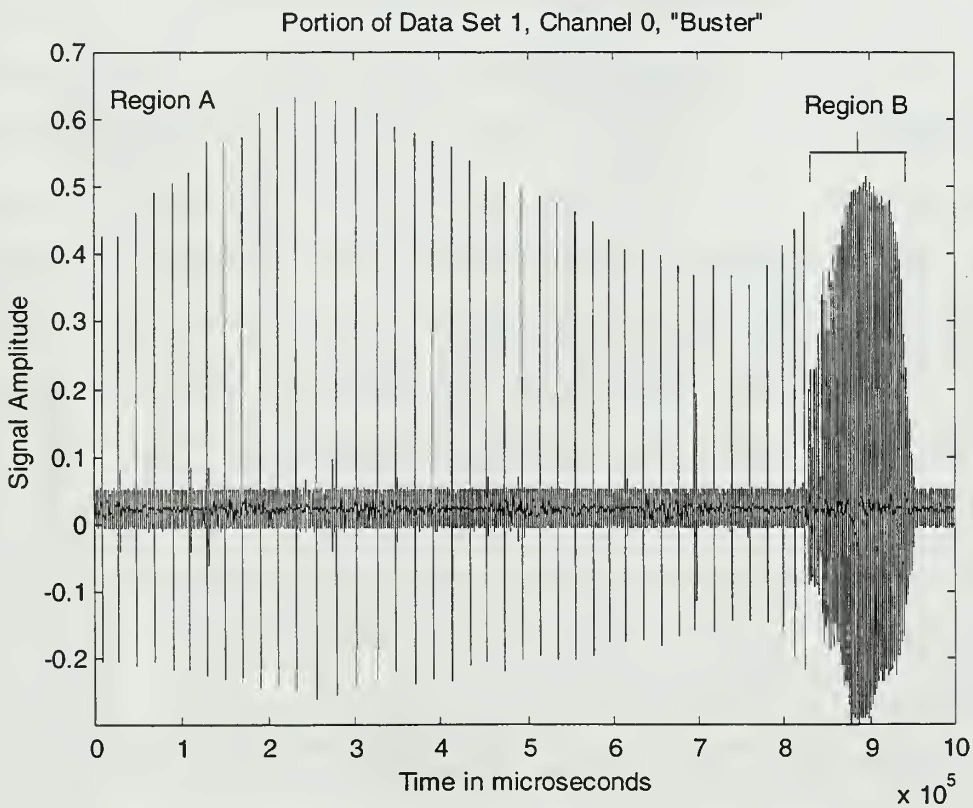


**Figure 11.** Time Series Data Set Used to Compute FFT's, Dolphin "Buster."

Signals were analyzed from the data set in Figure 11, from both Region A and Region B. In this figure, it is clear that the Dolphin dramatically decreased the period of individual clicks. This decrease coincides with an apparent localization of the target by the Dolphin on video. The data set had a distinct asymmetric structure, but it was a result of the Dolphin's transmission and not an error in data acquisition or signal processing. Figure 12 is an example of one time series plot of a single click from Region A, and figure 13 is an example of a single click from Region B.

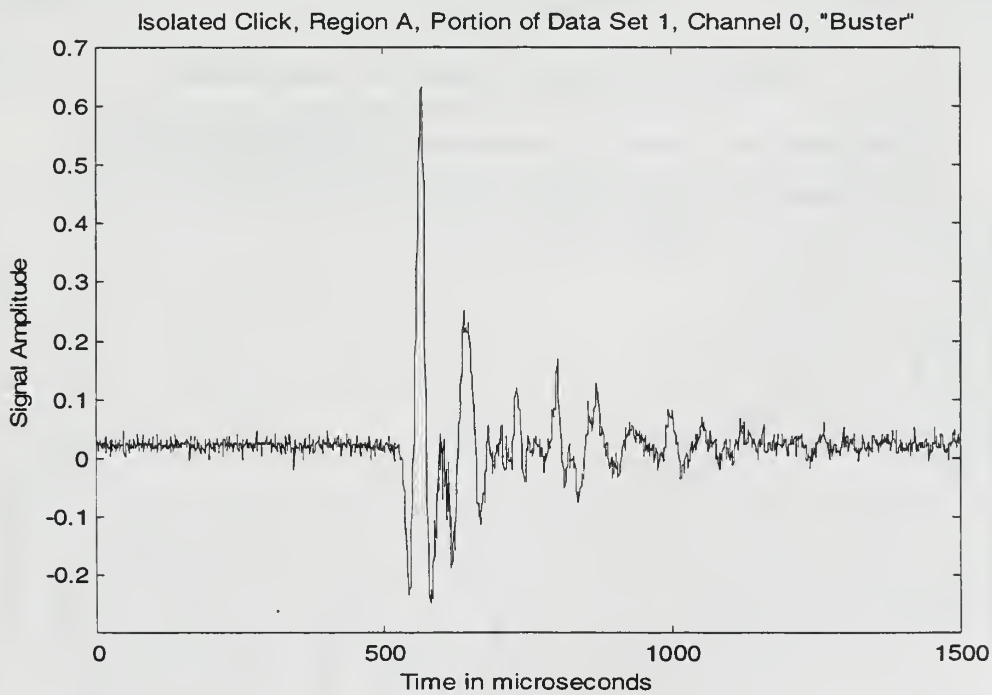


**Figure 12.** Single Click from Region A of Dolphin "Buster" Data Set.

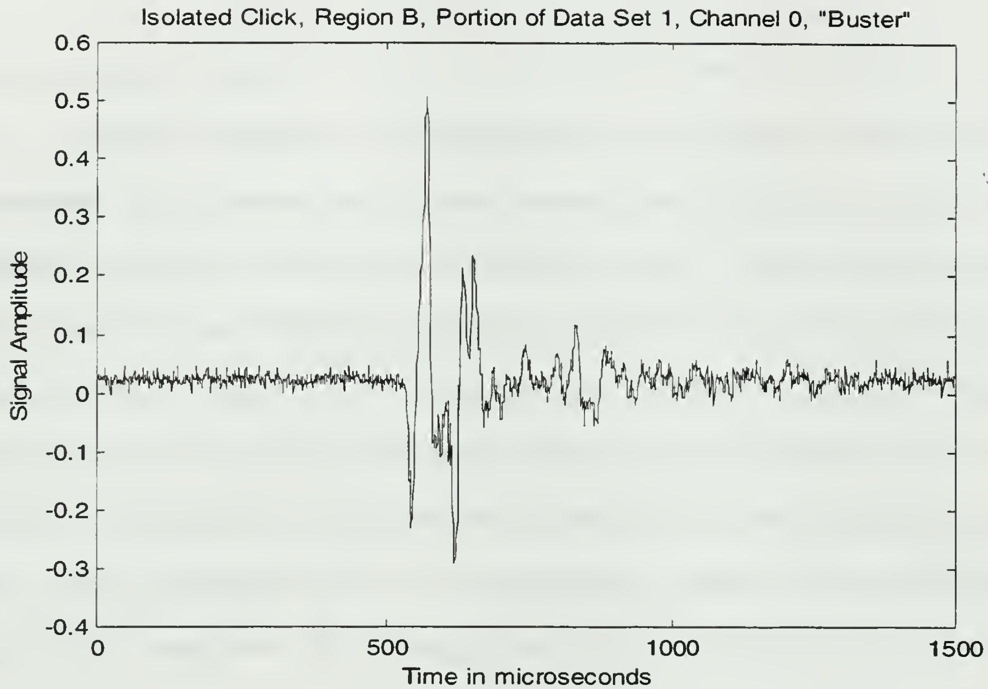


**Figure 13.** Single Click from Region B of Dolphin "Buster" Data Set.

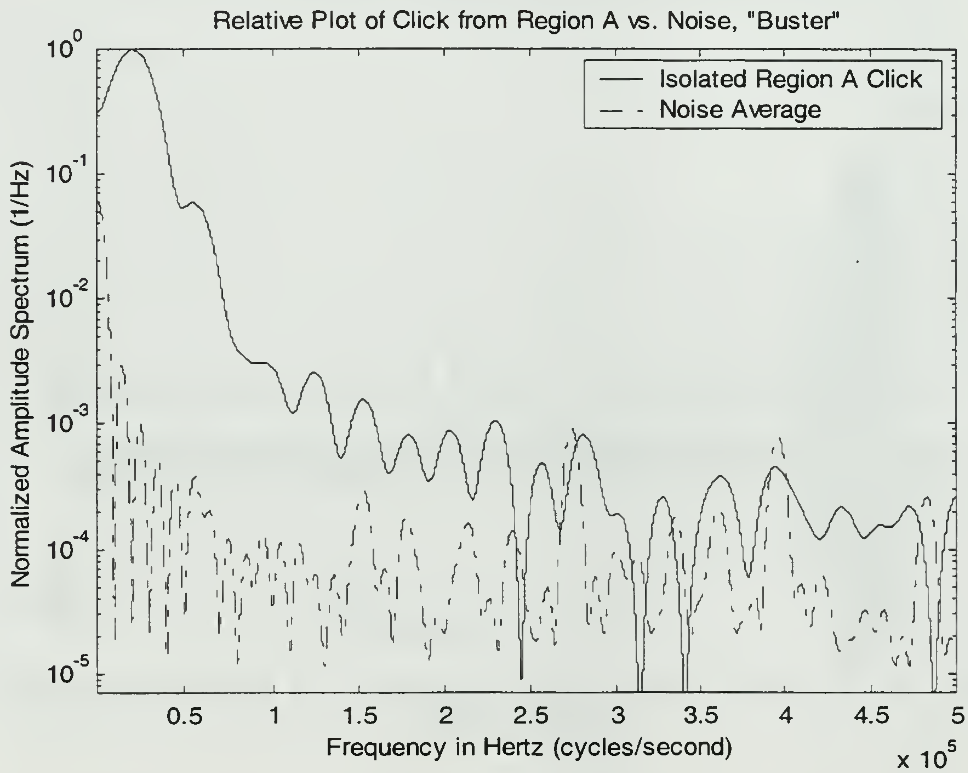


**Figure 14.** FFT of Isolated Click from Region A vs. Noise, Dolphin "Buster."

Figure 14 displays the FFT of an isolated click, constructed by gating out noise and reverberation, and the noise present during recording. The signal has a large amount of energy at frequencies below 100kHz, with the peak at 45kHz. Some additional energy exists from 100-200kHz, but to a much less extent. Another region of signal excess can be found between 400-500kHz.

Figure 15 illustrates the comparison between the frequency response for a click with reverberation and the background noise. In this data set, the signal with reverberation had a frequency spectrum very similar to the isolated click. The obvious difference is additional energy in the 275-350kHz band.

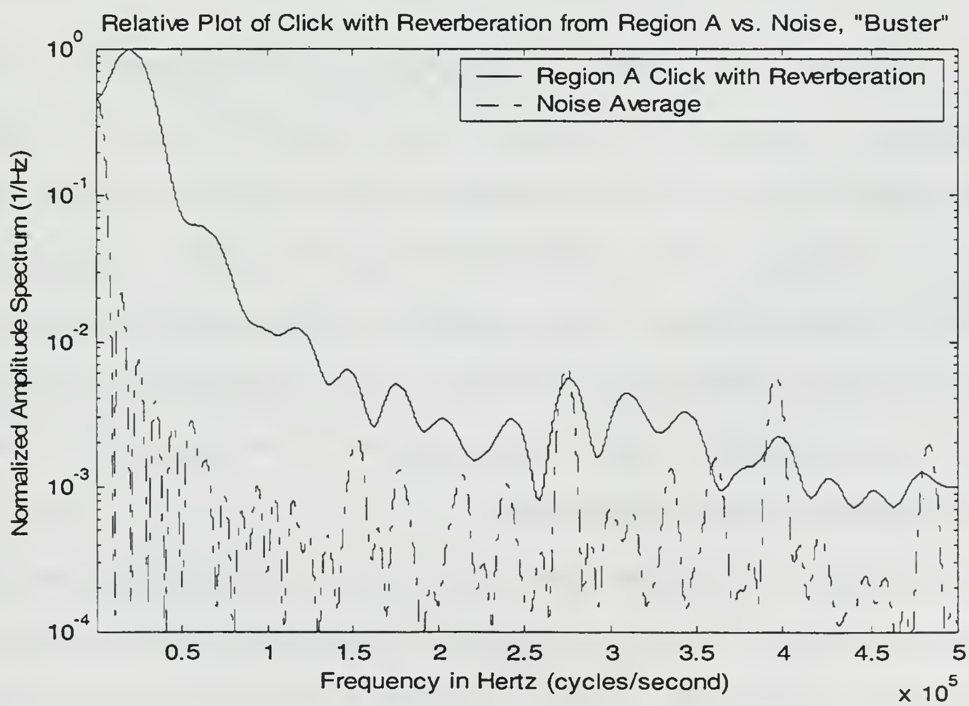


**Figure 15.** FFT of Single Click with Reverberation from Region A vs. Noise, Dolphin "Buster."

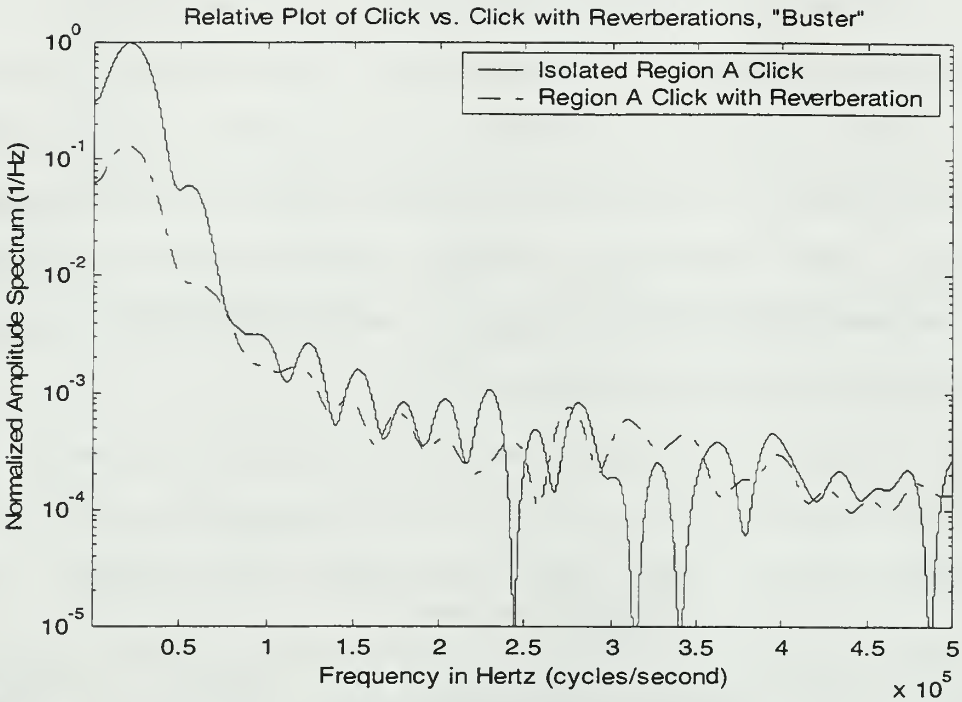


**Figure 16**. FFT of Single Click from Region A vs. Isolated Click with Reverberation from Region A, Dolphin "Buster."

Figure 16 clearly displays the differences found in processing the isolated click, and processing the click with reverberation. The isolated click has more of its signal strength in the frequencies below 75kHz, while the click with reverberation had a small content enhancement in the band from 300kHz to 350kHz. The isolated click is similar to a large cycle of a sine wave, so the lower frequency content was expected.

Next, the same data processing was performed on clicks from Region B of the "Buster" data set. Figure 17 is the frequency spectrum of an isolated click found in Region B vs. the same noise spectrum used in Region A processing.

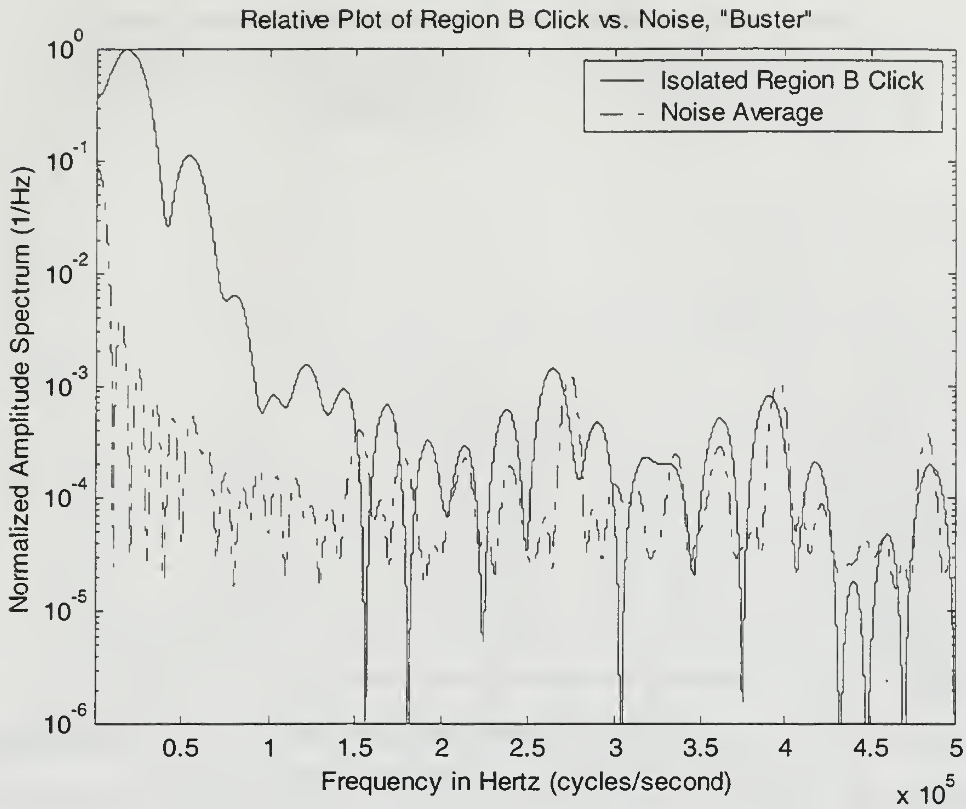


**Figure 17.** FFT of Isolated Click from Region B vs. Noise, Dolphin "Buster."

Figure 17 shows a good signal to noise ratio up to 150kHz, but little signal excess at higher frequencies. This plot is of an isolated click, so the higher frequencies, again, were not expected. However, figure 18 shows the click with reverberation, and it had significant energy up to 200kHz, at 300Khz and between 400-475kHz.

Figure 19 displays the differences between frequency spectra of the isolated click and the single click with reverberation. As with the Region A data, Region B isolated clicks had more energy in the lower frequencies, while clicks with reverberation data were above the noise in the higher frequencies.

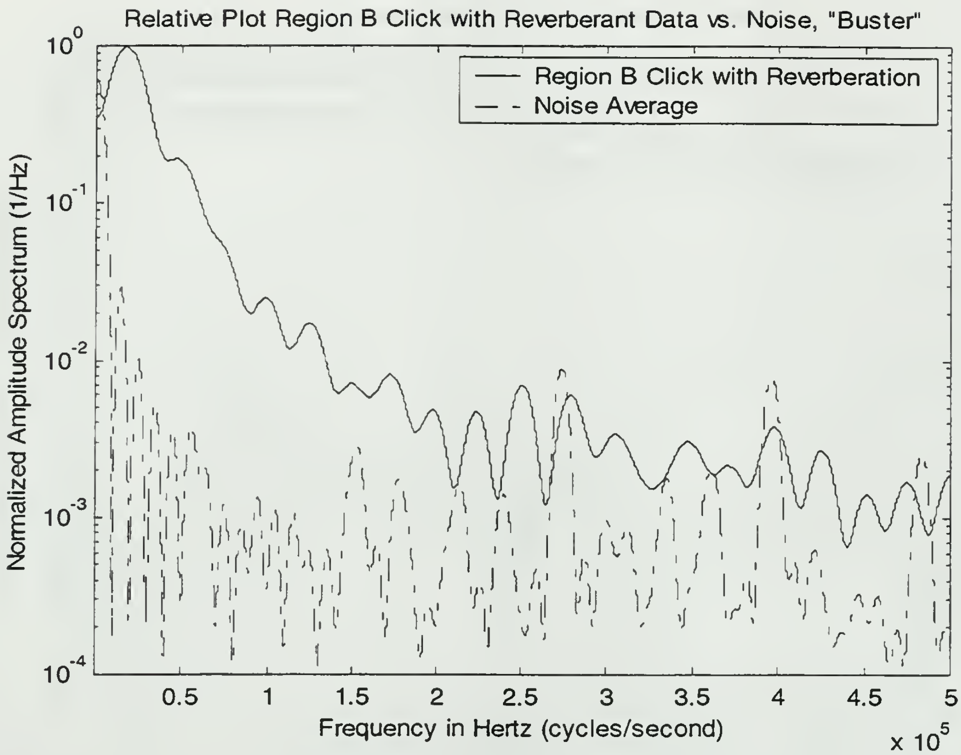


**Figure 18.** FFT of Single Click with Reverberation from Region B vs. Noise, Dolphin "Buster."

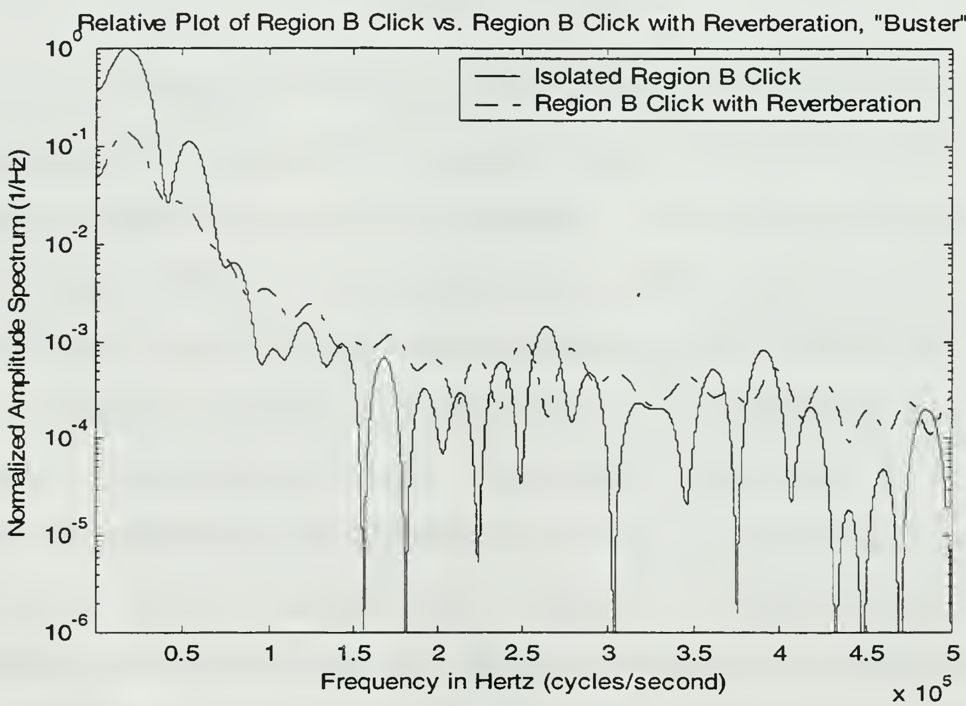


**Figure 19.** FFT of Isolated Click from Region B vs. Single Click with Reverberation from Region B, Dolphin "Buster."

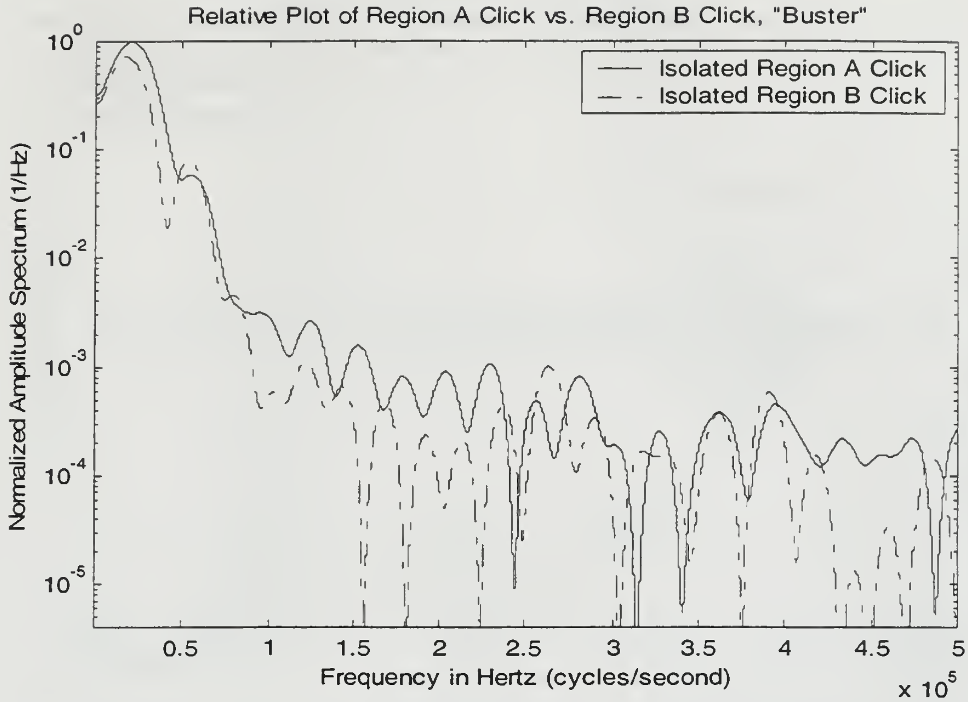


**Figure 20.** FFT of Isolated Click from Region A vs. Isolated Click from Region B, Dolphin "Buster."

Figure 20 illustrates the contrast between isolated clicks from the two separate regions. The isolated click from region A appeared to have had a higher signal level, and generally had somewhat more frequency content than the isolated click from region B.

Analysis of the clicks with their reverberation data, from both regions, showed slight differences in both signals, as shown in figure 21. Generally, the two frequency plots are very similar and no conclusion can be made about the sonar capabilities of the click from region A over the click from region B.

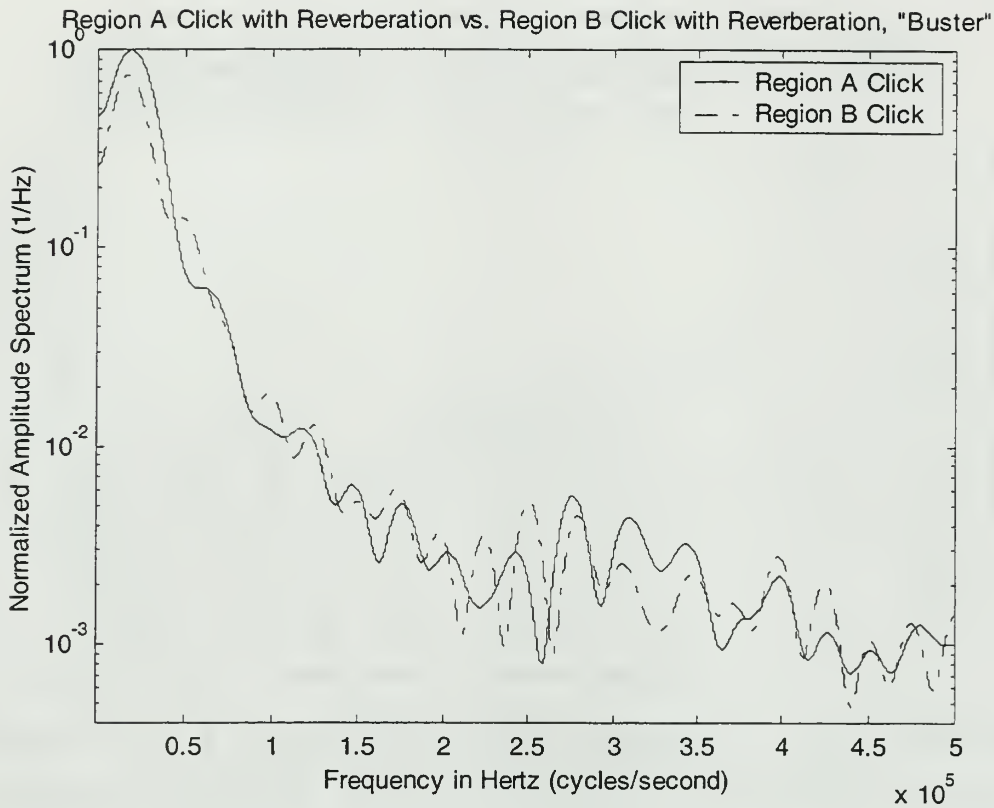


**Figure 21.** FFT of Single Click with Reverberation from Region A vs. Isolated Click with Reverberation from Region B, Dolphin "Buster."

### *c. Processed data from Dolphin "Nino"*

Figure 21 displays the portion of the time series data from the Dolphin "Nino" that was used for FFT testing. It was selected due to the decrease in click period, and exceptionally high signal to noise ratio. While there were significant differences in Regions A and B for Dolphin "Buster," the Dolphin "Nino" did not significantly vary its signals from regions of high click period to low click period.

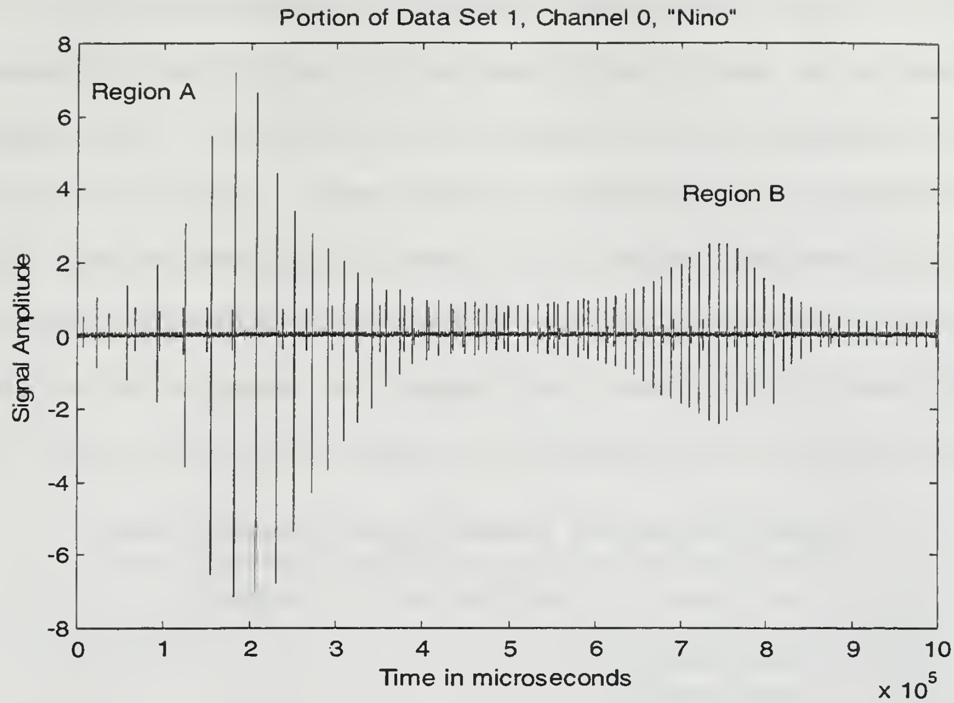


**Figure 22.** Time Series Data Set Used to Compute FFT's, Dolphin "Nino."

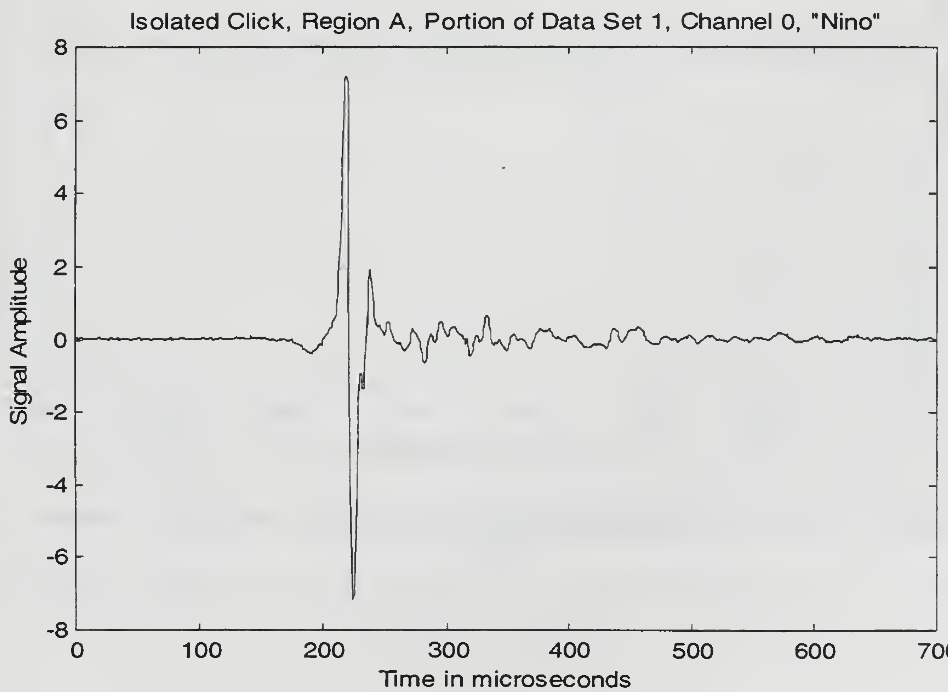


**Figure 23.** Single Click from Region A of Dolphin "Nino" Data Set.

Figure 23 more closely illustrates a single click from Region A, where the click period was larger. Figure 24 shows a single click retrieved from Region B, where "Nino" had slightly decreased his click period. As in "Buster's" data, this Dolphin appeared to have found the target at the time the periodicity of the clicks was changed, indicating he switched to a higher rate scan to, most likely, gather more data about the target.

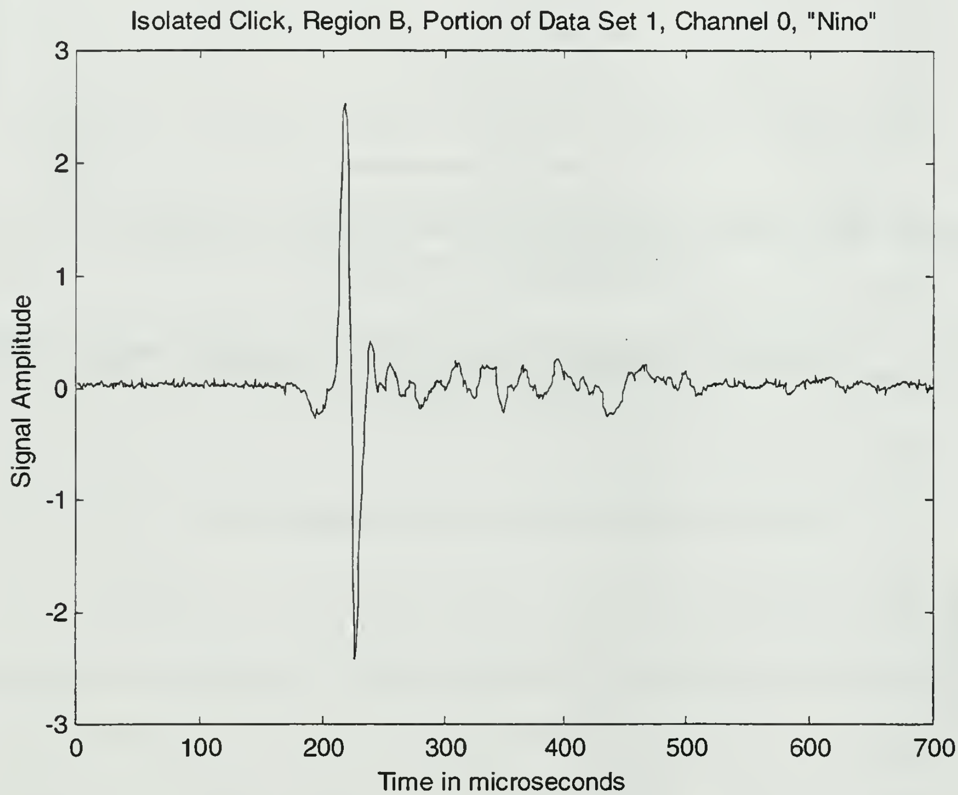


**Figure 24.** Single Click from Region B of Dolphin "Nino" Data Set.

Figure 25 illustrates the value of a high signal to noise ratio. This figure shows the signal several orders of magnitude above the noise signature, across the entire frequency spectrum. The click energy at all frequencies was unexpected, and could be due to an error; however, no error could be determined. The peak remains approximately 47kHz, twice the frequency of the signals recorded from "Buster" which had a frequency peaks at 20Khz.

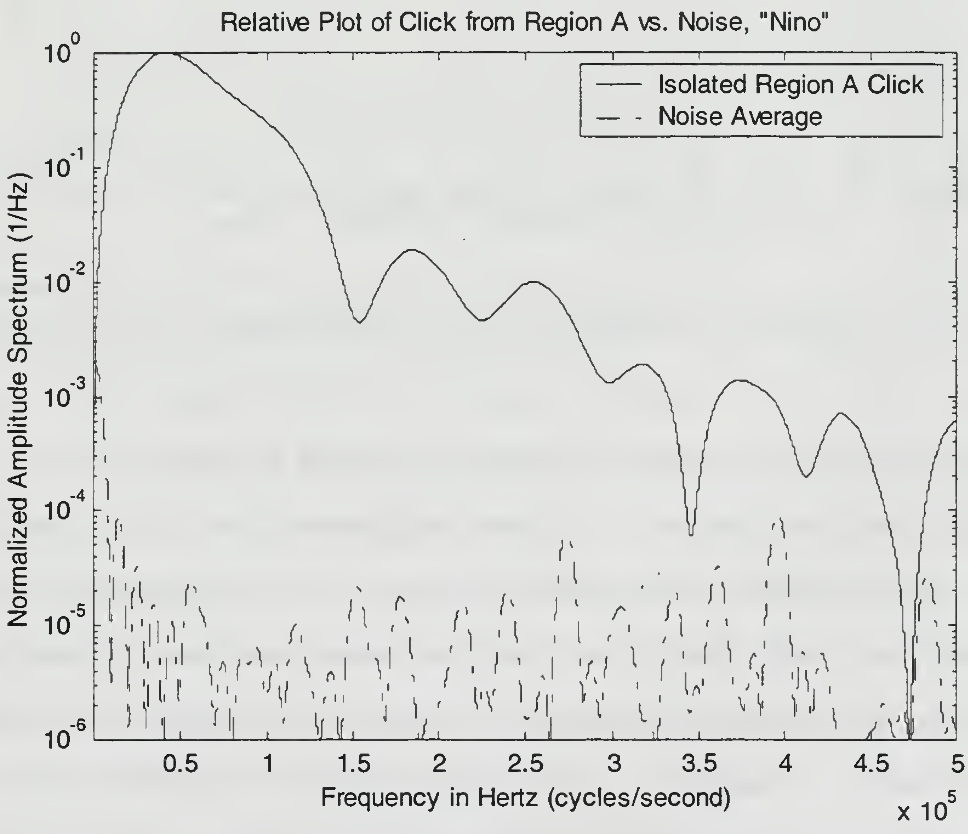


**Figure 25.** FFT of Isolated Click from Region A vs. Noise, Dolphin "Nino."

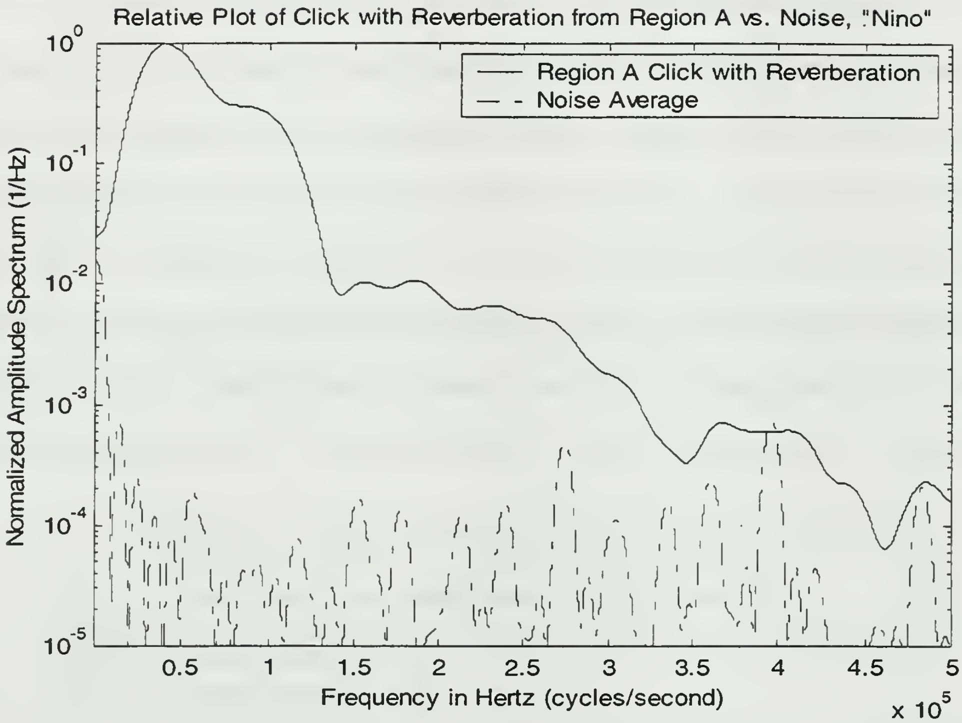


**Figure 26.** FFT of Single Click with Reverberation from Region A vs. Noise, Dolphin "Nino."

Figure 27 displays the comparison of frequency spectra of an isolated click to the same click with reverberant data. This figure may lend credibility to the accuracy of the data. It was expected that the isolated click would have the majority of its energy at lower frequencies, and the click with reverberant data would show less energy at lower frequencies and more energy at higher frequencies. Analysis of additional data sets would be required to determine the validity of the presented data set from Dolphin "Nino."

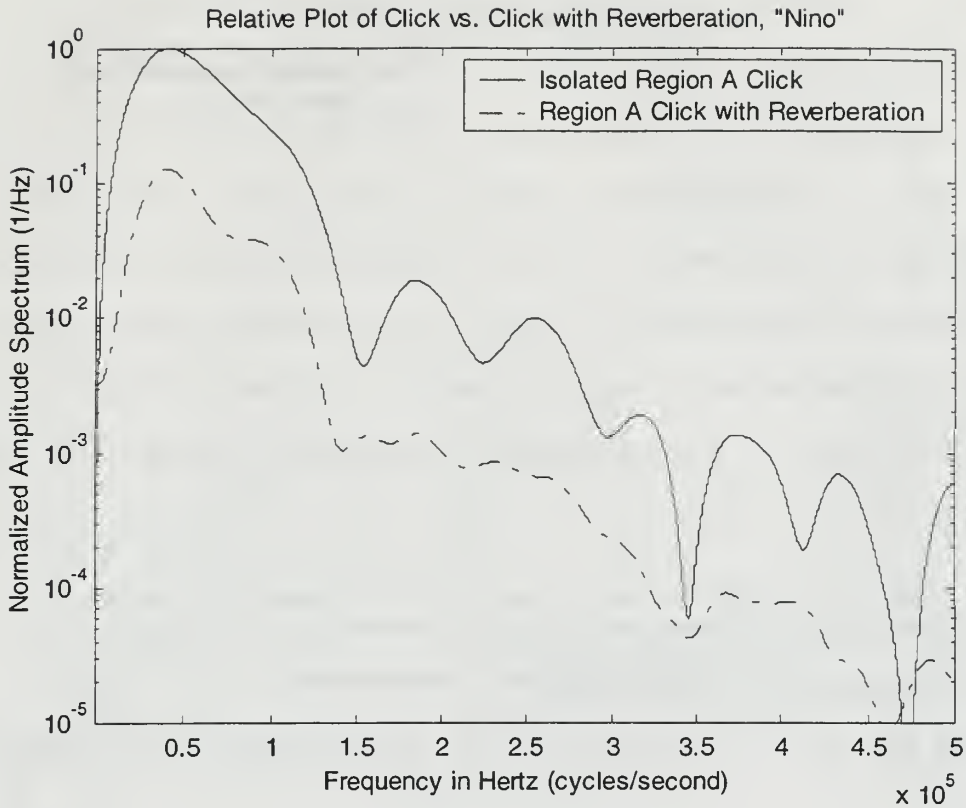


**Figure 27.** FFT of Isolated Click from Region A vs. Isolated Click with Reverberation from Region A, Dolphin "Nino."

Figure 28 depicts the frequency spectra of an isolated click from Region B of the "Nino" data set and is more representative of signals analyzed in other data sets. The peak frequency has dropped to 30kHz for an isolated click in region B, but some additional energy is found at 200kHz, 250kHz, 300kHz and 450kHz. However, the signal peaks resemble the noise peaks and may be a function of noise present in the click. Figure 29 illustrates the FFT of a single click and reverberation versus the background noise spectrum from Dolphin "Nino."

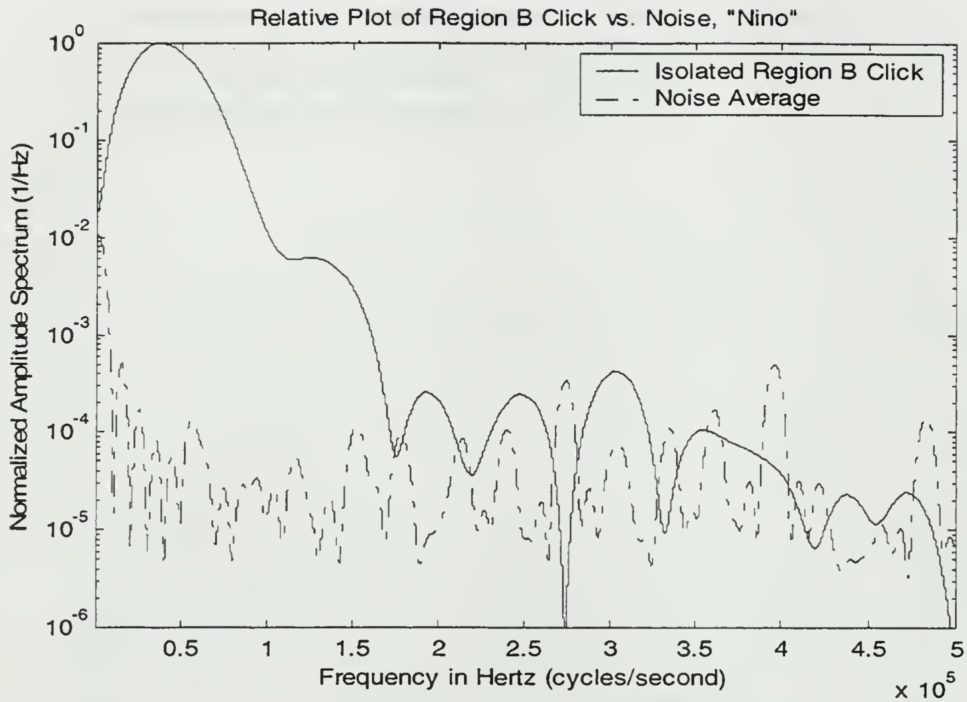


**Figure 28.** FFT of Isolated Click from Region B vs. Noise, Dolphin "Nino."

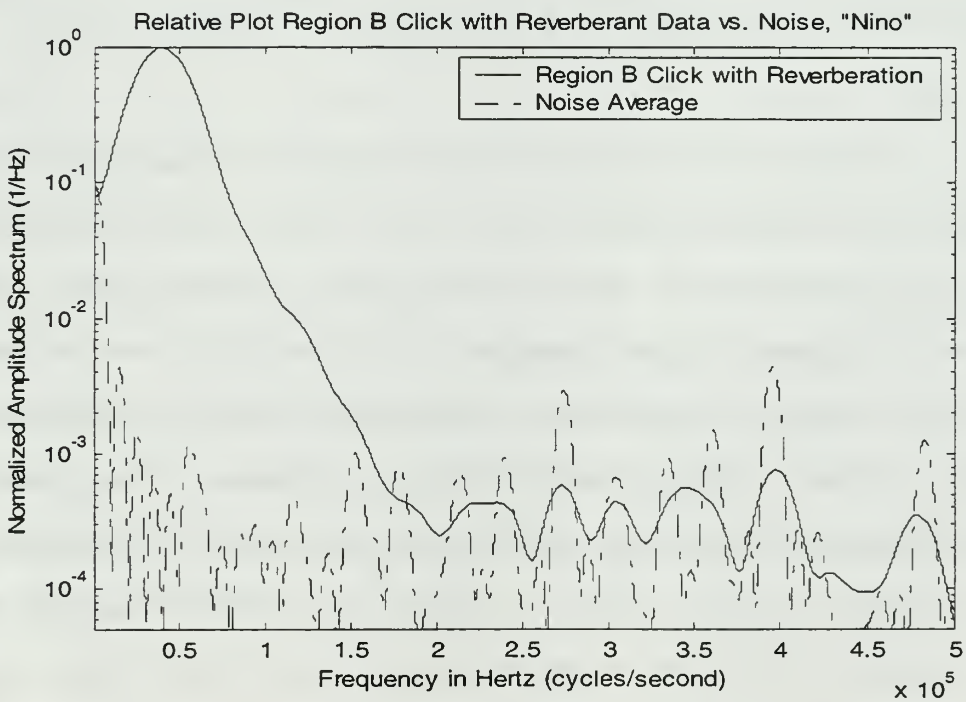


**Figure 29.** FFT of Single Click with Reverberation from Region B vs. Noise, Dolphin "Nino."

Figure 30 shows the differences between the FFT's of an isolated click and a click with the reverberation data. The shape of the curves was as expected. The isolated click FFT had a single large peak in the lower frequencies, while the FFT of the click with reverberant data had less energy in the lower frequencies, but more in the higher frequencies. These general characteristics were found in every data set analyzed, and in both species studied.

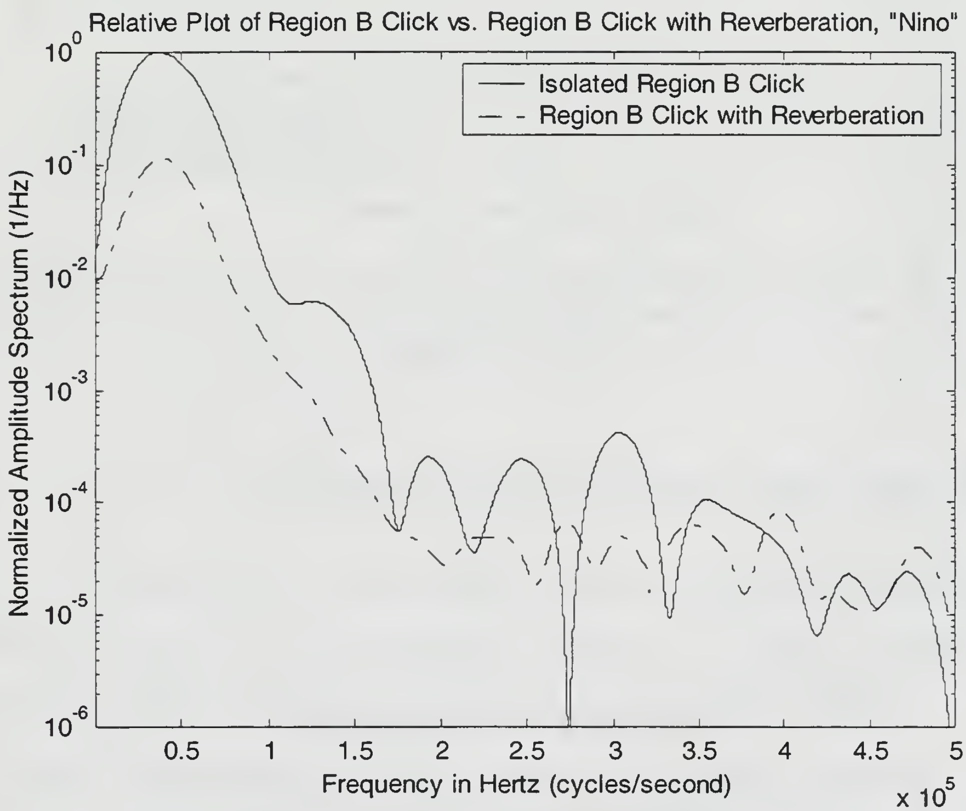


**Figure 30.** FFT of Isolated Click from Region B vs. Single Click with Reverberation from Region B, Dolphin "Nino."

Figures 31 and 32 illustrate the interesting finding that peak click frequency for this animal decreased as the click period decreased. This phenomenon was not observed in the hearing impaired Dolphin and may be one of the manifestations of the disability. Also, it is clear that the higher amplitude signals from region A carry well above the noise, and above the signals emitted in region B. Additional data sets should be analyzed to determine if these phenomena are unique or common to Dolphin behavior.

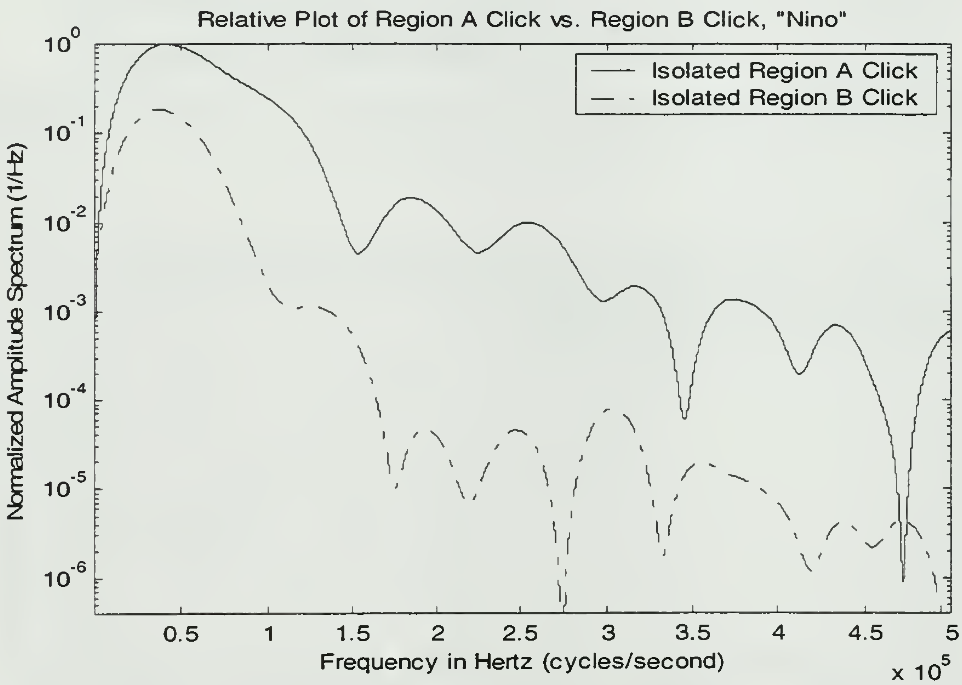


**Figure 31.** FFT of Isolated Click from Region A vs. Isolated Click from Region B, Dolphin "Nino."

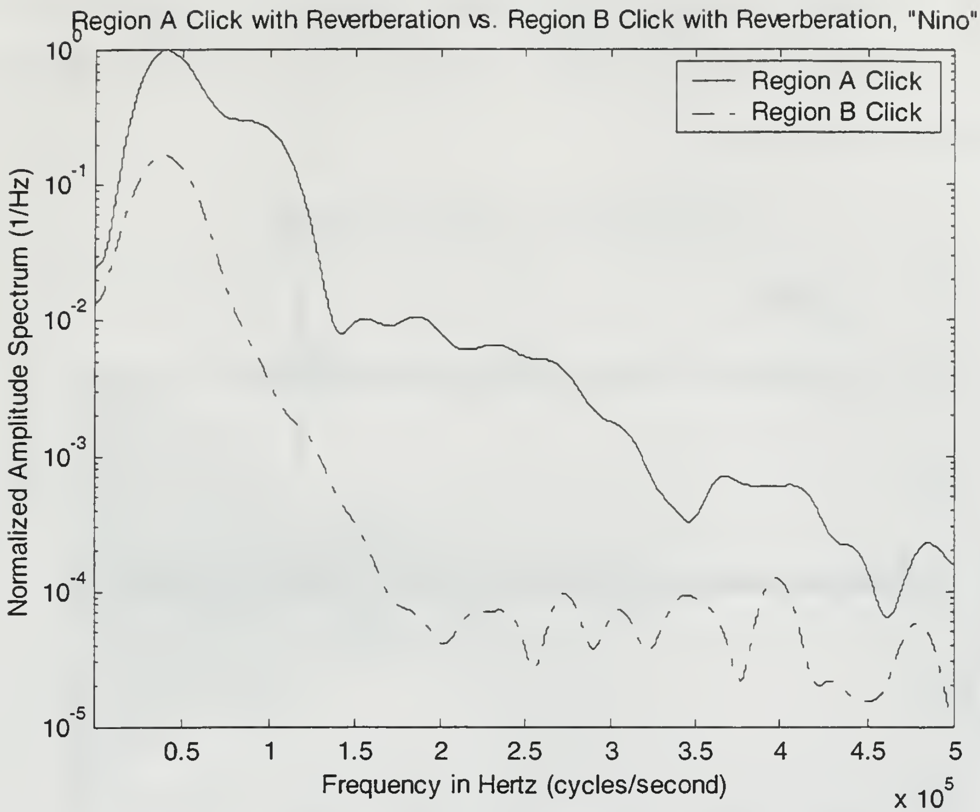


**Figure 32.** FFT of Single Click with Reverberation from Region A vs. Single Click with Reverberation from Region B, Dolphin "Nino."

#### *d. Processed Data from Beluga Whale "Muk-Tuk"*

"Muk-Tuk," the Beluga Whale, was also recorded to compare with the Bottlenose Dolphins. Above water, the Beluga clicks seem to be much stronger than Dolphin clicks, so it was believed that the signals would be stronger in the water as well. While his signal amplitudes were generally higher than the Dolphin signals, the following figures illustrate the characteristics of "Muk-Tuk's" sonar clicks when click periodicity was altered. Figure 33 presents the data used in FFT processing. Region A in figure 33 is an

area of widely spaced clicks and region B is an area of closely space clicks, much like the Dolphin “Buster” displayed in figure 7.

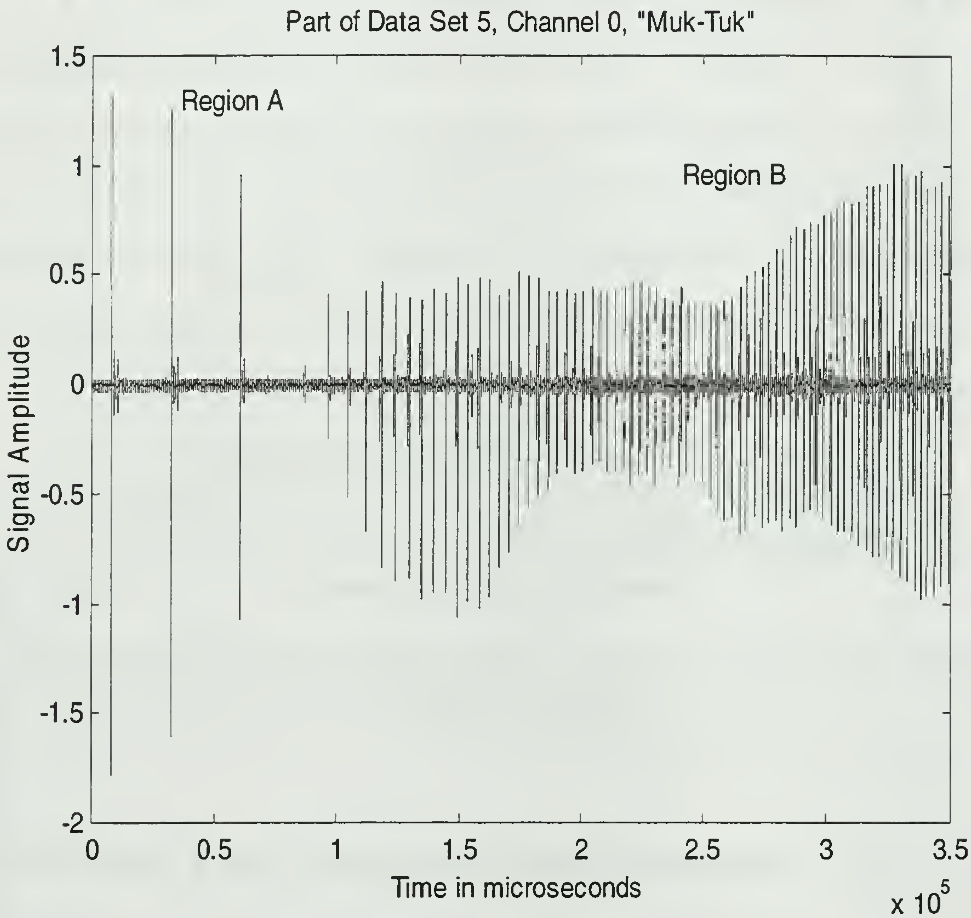


**Figure 33.** Time Series Data Set Used to Compute FFT's, Whale "Muk-Tuk."

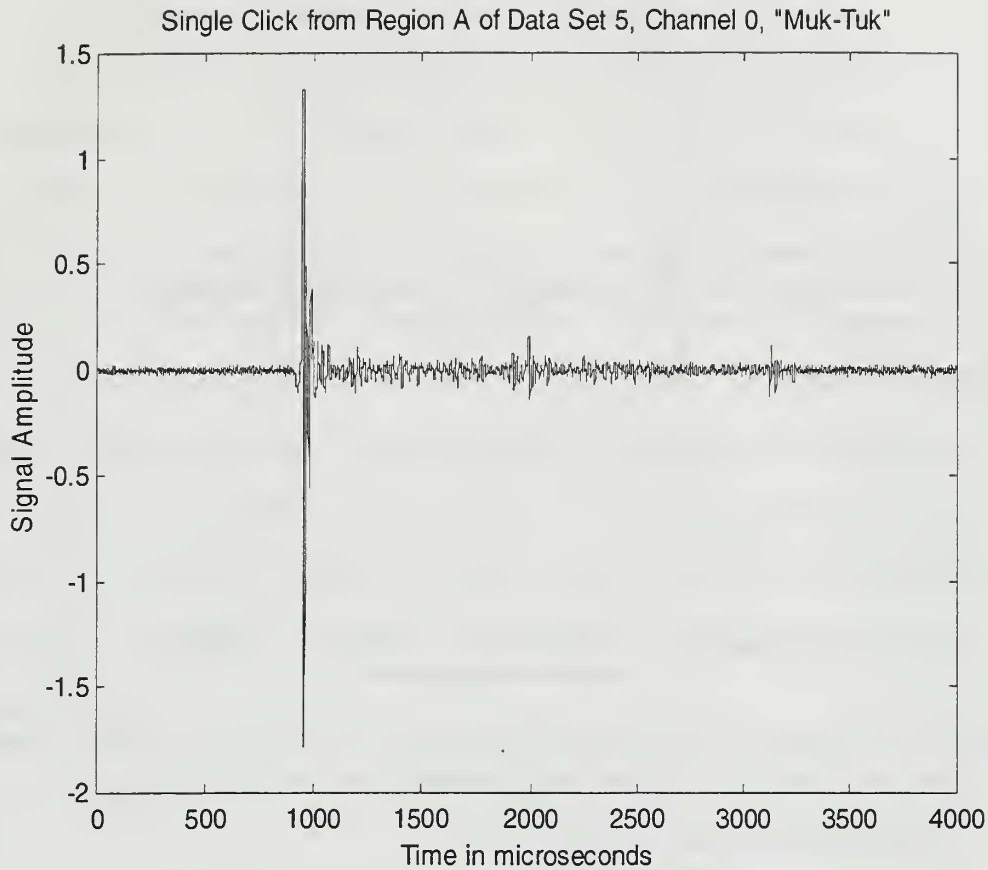


**Figure 34.** Single Click from Region A of Beluga Whale "Muk-Tuk" Data Set.

Figure 34 gives a better view of a click from region A of figure 33. Interesting secondary signals were observed 1 and 2 milliseconds after the initial click. The experimental apparatus utilized for recording "Muk-Tuk's" signals was unmodified from the previous experiments, so equipment and environmental reflections were not determined to be the cause. The same structures were observed in the clicks from region B, illustrated in figure 35. Additional research could determine the nature of these secondary clicks.

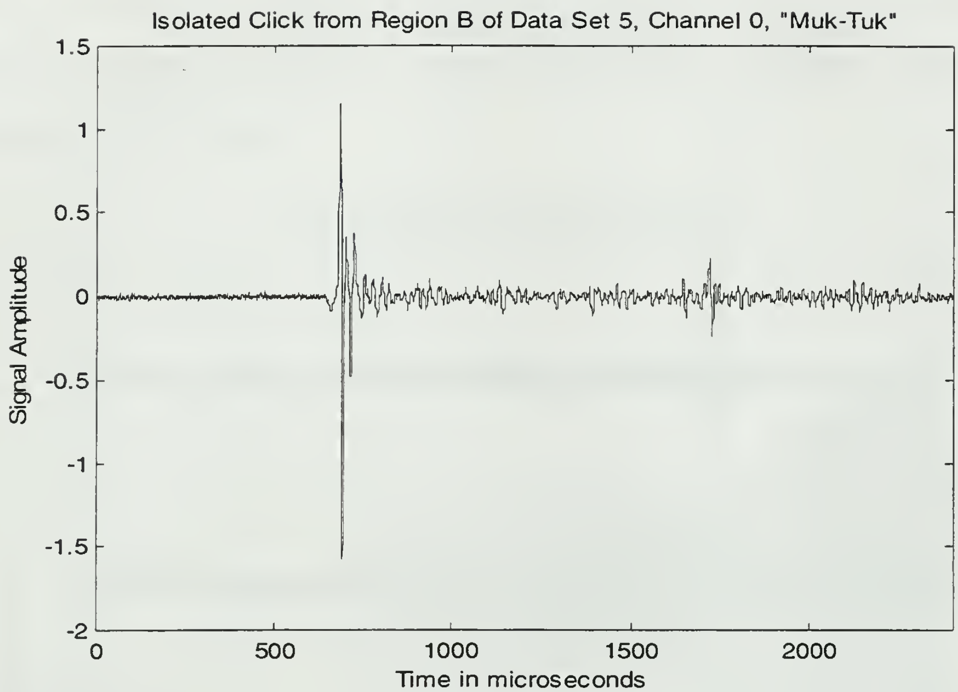


**Figure 35.** Single Click from Region B of Beluga Whale "Muk-Tuk" Data Set.

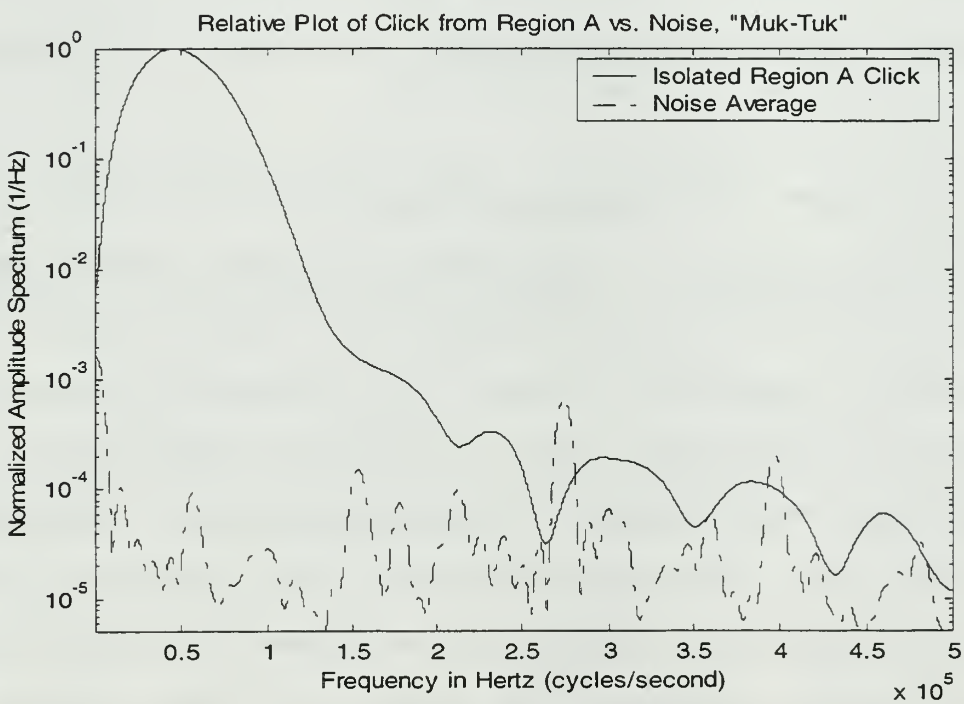


**Figure 36.** FFT of Isolated Click from Region A vs. Noise, Beluga Whale "Muk-Tuk."

Figure 36 demonstrates that the isolated click transmitted by the Beluga Whale is very similar to the two Bottlenose Dolphins. The majority of the energy is center at 40-50kHz, while only a small amount above the noise is present at the higher frequencies. However, when the FFT of the click and reverberation is plotted against background noise, the spectrum of the higher frequencies nearly matches the noise spectrum. (Fig. 37) It is apparent from this region A data set that the only significant sonar energy was confined to the lower frequency click portion of the transmission.

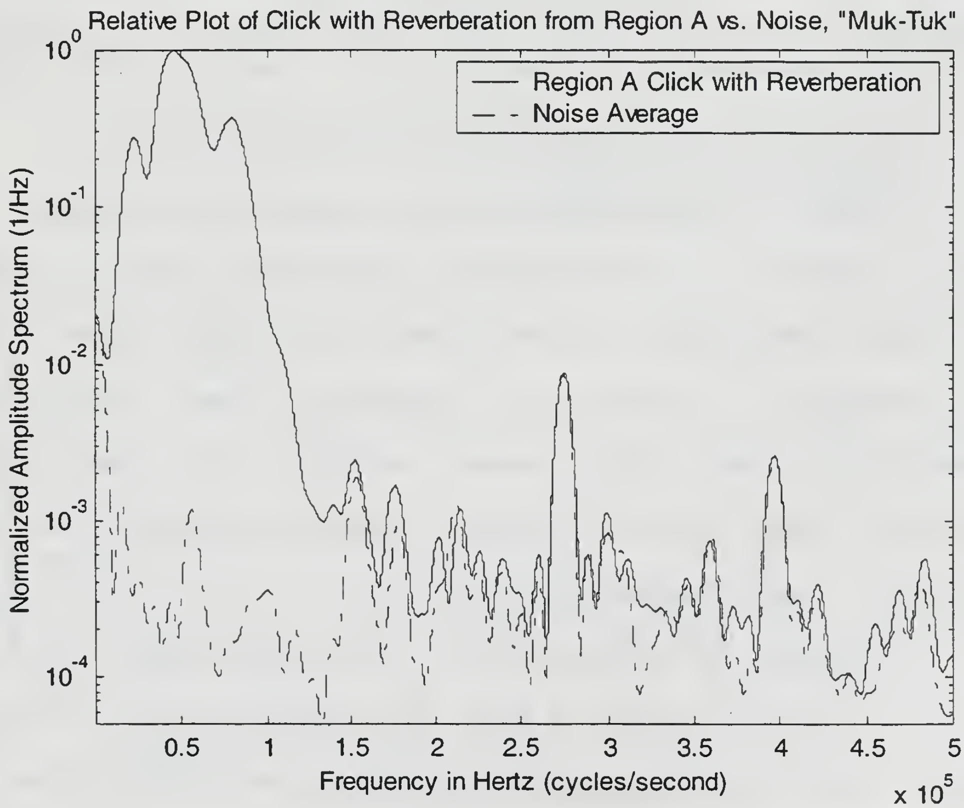


**Figure 37.** FFT of Single Click with Reverberation from Region A vs. Noise, Beluga Whale "Muk-Tuk."

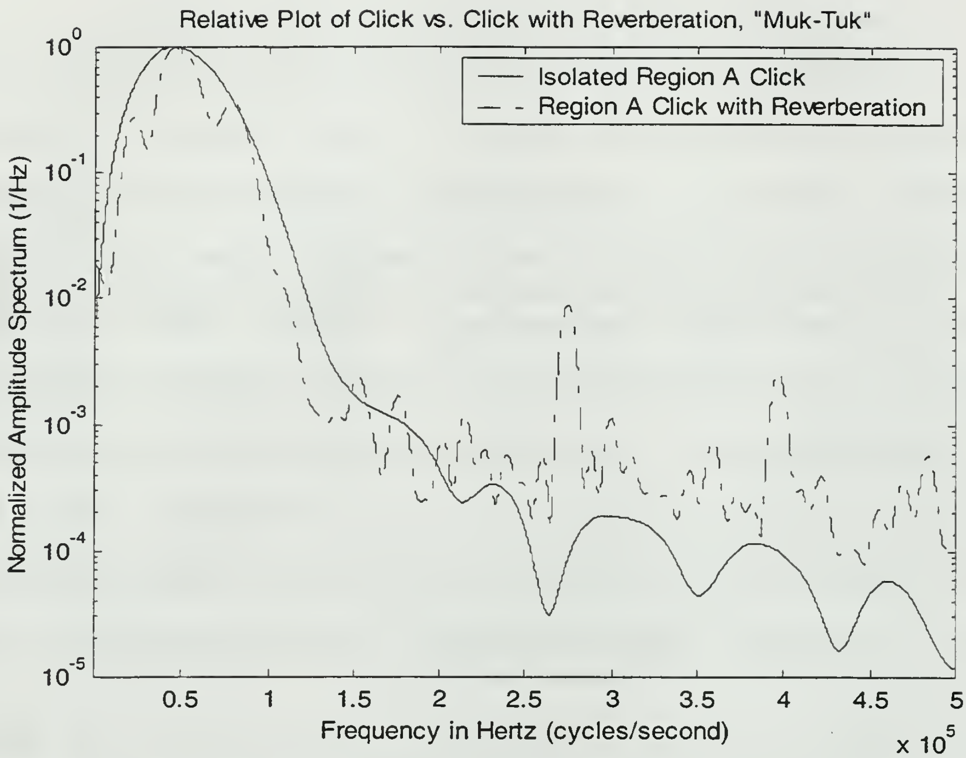


**Figure 38.** FFT of Isolated Click from Region A vs. Single Click with Reverberation from Region A, Beluga Whale "Muk-Tuk."

Figure 38 illustrates the comparison between the frequency spectra of an isolated click from region A and a click with reverberant data from the same longer click period region. While it appears the click with reverberation had much more energy in the higher frequencies, bear in mind that it nearly matched the noise spectrum for that frequency range.

Figure 39 presents an isolated click from the short click period region B and the ambient noise. Several frequency bands show positive energy in the signal above the noise signature, and the peak frequency band has been widened from 100kHz to 150kHz.

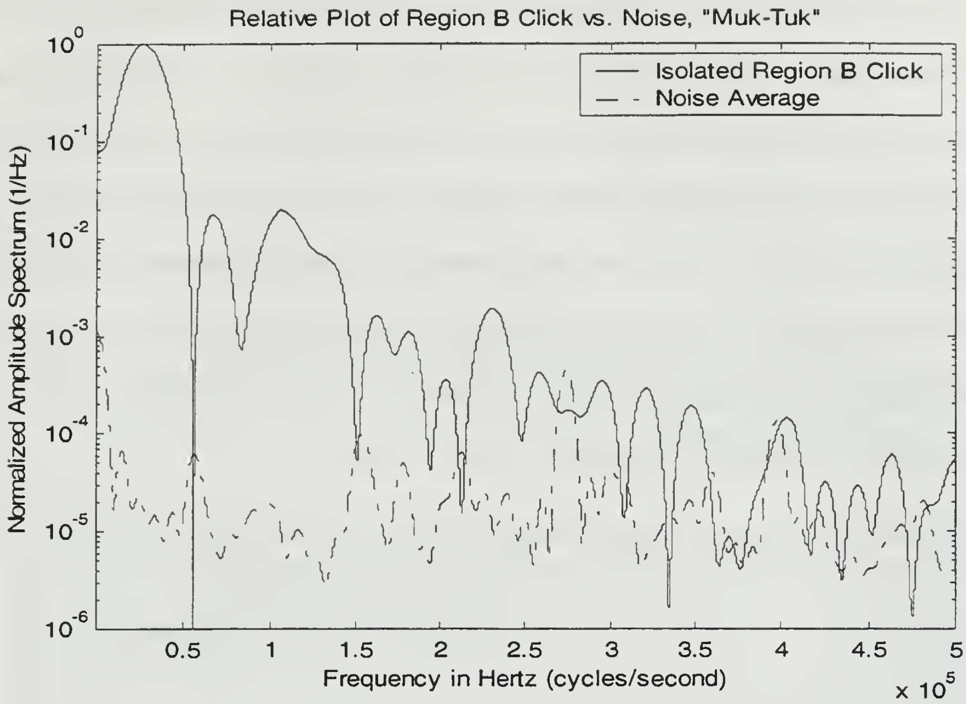


**Figure 39.** FFT of Isolated Click from Region B vs. Noise, Beluga Whale "Muk-Tuk."

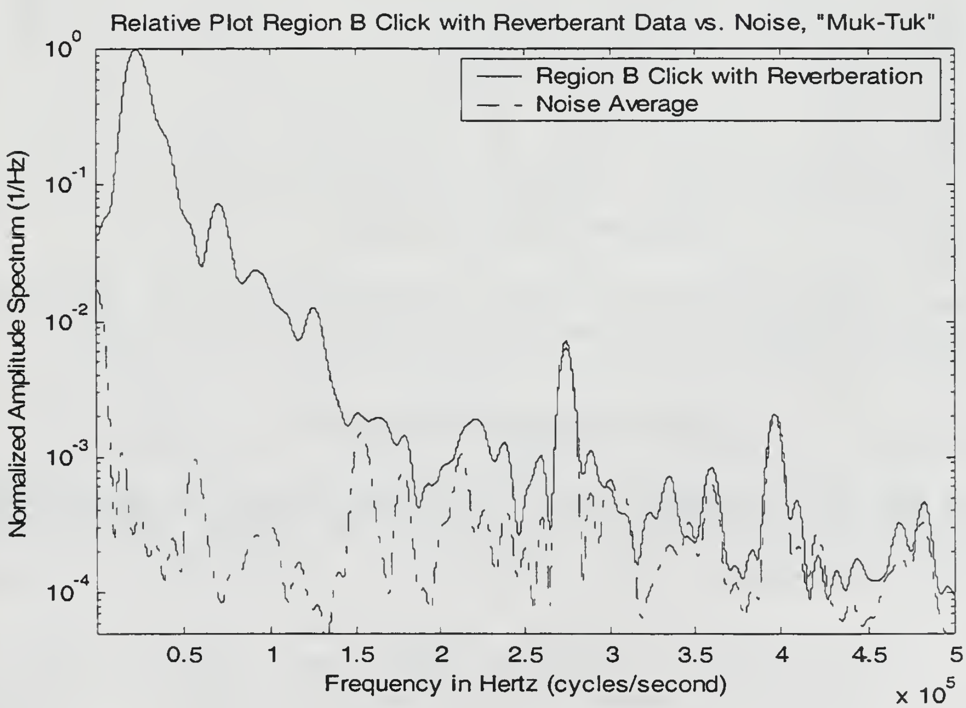


**Figure 40.** FFT of Single Click with Reverberation from Region B vs. Noise, Beluga Whale "Muk-Tuk."

Figure 40 illustrates a similar widening of the peak frequency band, as in figure 39. A significant observation of figure 40 is the correspondence of the signal FFT plot to the noise FFT plot. It appears that the reverberation does not add any significant signal energy to the isolated click, and would most likely be difficult for the animal to recover any signal information from the reverberation region of his transmission.

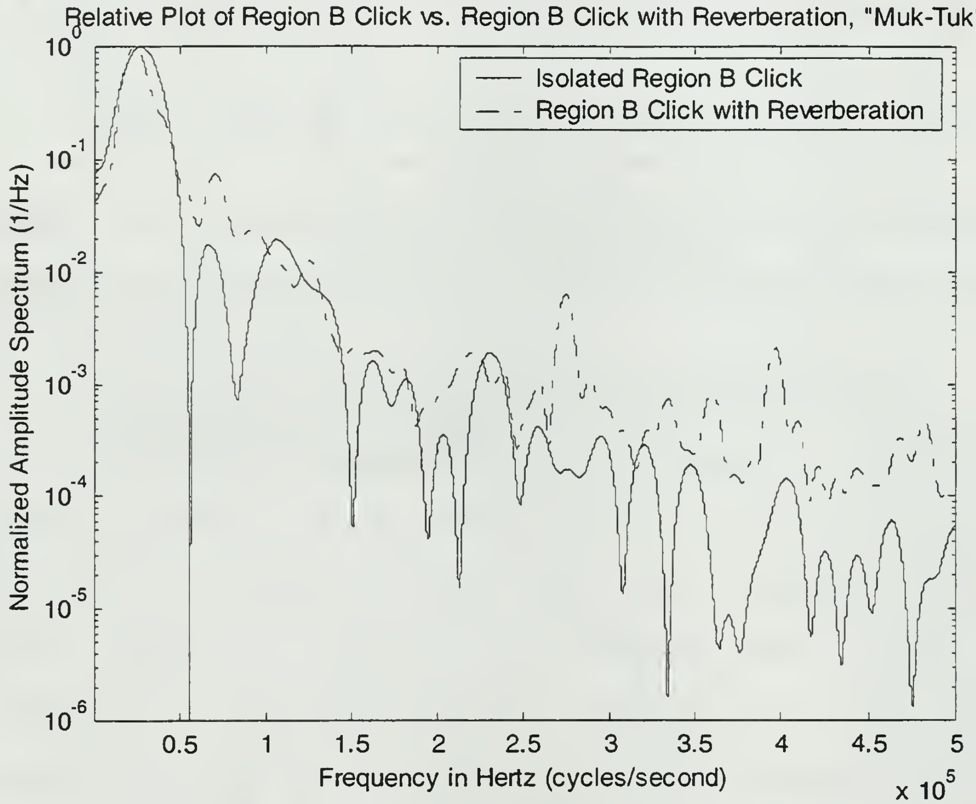


**Figure 41.** FFT of Isolated Click from Region B vs. Single Click with Reverberation from Region B, Beluga Whale "Muk-Tuk."

Figure 41 illustrates additional signal energy is present in the click reverberation between 50kHz and 100kHz. The figure seems to indicate that significant energy is

present above 250kHz, however, that plot nearly matches the diagram of the ambient noise spectrum. The similarities of the two plots in figure 41 make other definitive statements about a difference between the isolated click and a single click with reverberation impossible.

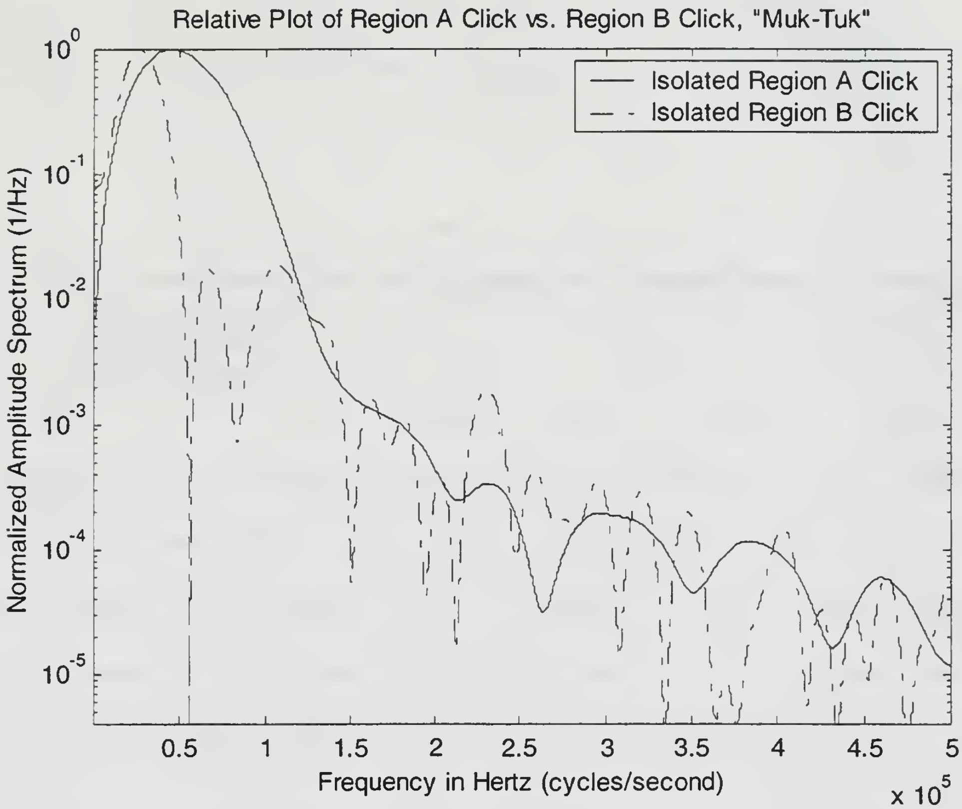


**Figure 42.** FFT of Isolated Click from Region A vs. Isolated Click from Region B, Beluga Whale "Muk-Tuk."

Figure 42, which compares isolated clicks spectra from region A and region B, clearly shows a shift in peak frequency from 50kHz to 25kHz. This phenomenon was also observed in the Bottlenose Dolphin "Nino," with normal hearing, but not in the hearing impaired Dolphin "Buster."

Interestingly, both "Muk-Tuk" and "Nino" showed shifts from 50kHz to 25kHz.

Figure 43 displays the same peak frequency shift when FFT's of clicks with reverberant data from different regions are compared. Also found in figure 43 is the pattern of short period clicks with lower energy in the lower frequencies and higher energy in the higher frequencies.

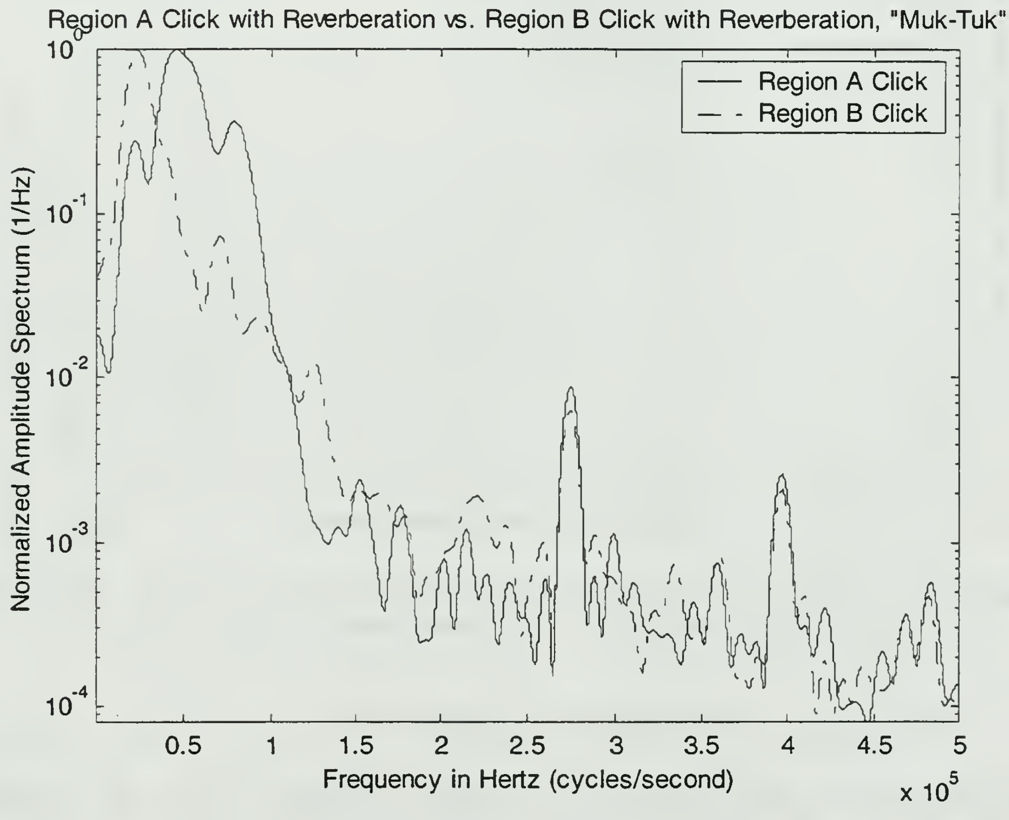


**Figure 43.** FFT of Single Click with Reverberation from Region A vs. Single Click with Reverberation from Region B, Beluga Whale "Muk-Tuk."

#### *e. Noise*

A result of the close range of the transmitting Dolphins and high signal levels is a high signal to noise ratio, especially apparent in data sets from "Nino." The measure of signal level to background noise level is one way to ensure accurate data transmission. Signals that are very close in level to noise are very difficult to recover and analyze. Amplification cannot improve the signal to noise ratio, only boost both levels by the same relative amount, resulting in no net improvement. Figure 44 illustrates raw data of noise found between sonar clicks. Noise was introduced by Man-made and natural sounds in the San Diego Bay and by amplifier and data acquisition equipment within this system. The majority of noise in the higher frequency regions was introduced by experimental equipment such as amplifiers, data acquisition PCI card and the PC itself.

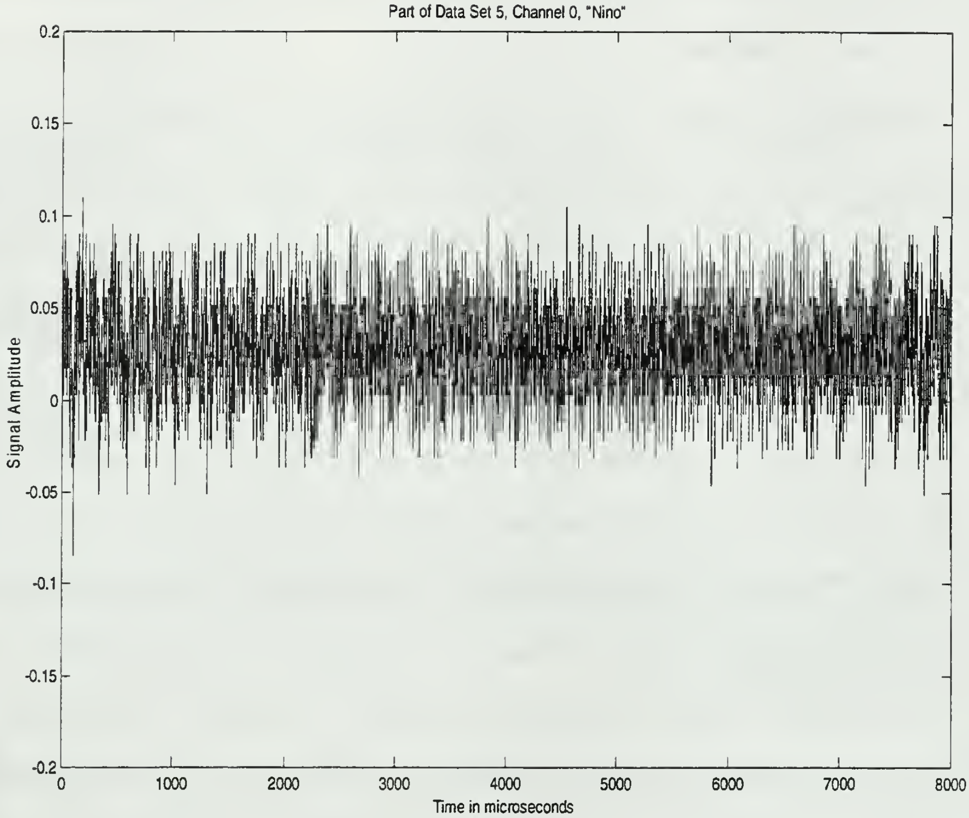


**Figure 44**. Time Series Plot of Experimental Noise.

As previously stated, all noise FFT processing used an average of 40 contiguous segments of noise present just prior to the click that was analyzed, due to the significantly larger length of noise data to click data. Noise segments were 100 microseconds in length, for a total data length of 4000 microseconds. This averaging was performed to gain an accurate picture of the noise frequency spectrum.

# IV. CONCLUSIONS AND RECOMMENDATIONS

Processing and analysis of the data recorded at SSC San Diego proved an immensely worthwhile task, however it presented more questions than answers. The data shows that Dolphins can modify click periodicity as desired, most likely to get a better sonar reflections of the target. During click periodicity decreases, it was noted that clicks were reduced in amplitude. Also, the peak frequency of an isolated click was reduced as click periodicity was reduced. However, the hearing impaired Dolphin did not reduce peak click frequency as he shortened click periodicity. The hearing impaired Dolphin's peak click frequencies were all below the lowest frequency of the other two animals.

The Dolphin's have the ability to vary the frequency and amplitude of each click, and the time between clicks. When data was analyzed in conjunction with video data, it appeared the Dolphins have more space between clicks and higher click frequency while "searching" for a target. It was observed that the Dolphin's locate a target and attempt to discriminate between it and other objects, such as the camera lens. As a result, the Dolphins dramatically reduced the time between clicks (click period), and the isolated click frequency was decreased.

This experiment may have errors due to the manner in which it was carried out. Recording sonar signals in the previously described environment is not ideal. The Dolphins

were given an easy task, to determine if an object, the target, was present in the water. They may not have used their full sonar capabilities to perform their relatively simple task. The trainer was asking the Dolphin to indicate "yes" or "no," and not to indicate the type or shape of material they were sensing. A more difficult task could force the subject animal to perform at the limit of its abilities.

The computer used to store the data proved to be the weak link in the system. It suffered frequent lock-ups and shutdowns due to the strain of high sampling rate placed upon it by the data acquisition program and hardware. Future experiments in this area should utilize a high speed CPU with abundant Rapid Access Memory (RAM) and plentiful disk storage space. Also, hard drives configured for fastest possible transfer speeds would be useful.

Viewing the video and comparing signals of the two receiving channels attained correlation between digital video and recorded sonar data. This method is far from accurate, but the lack of a timing link between the data and video prevented better synchronization. Future experimenters should design a camera that is linked to the data acquisition equipment for precise correlation.

Future research is needed to determine if the Dolphins use the reverberant region of the click, or the single click alone. This experiment demonstrated that the Dolphins do not possess high frequency components within an isolated

click, however, high frequency components were discovered in the reverberation that followed the single clicks. Application of the uncertainty principle would require the Dolphins use a much higher frequency signal than the isolated clicks presented here. If Dolphins do use higher frequencies, they must make some use of the reverberation portion of their transmission. However, Kamminga [Ref. 1] has published on this point, concluding that the reverberant portion of the Dolphin transmission is not a significant part of the animal's sonar. It is also possible that the Dolphins have the capability to process a lower frequency signal in a way that permits higher resolution regardless of the uncertainty principle.

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APPENDIX A

ITC-1089D TRANSDUCER CALIBRATION CURVES

One curve has been provided for each transducer for frequencies from 100kHz to 400kHz (figs. A1 and A2). The curve for frequencies below 100kHz was not generated using one of the two transducers in this experiment, but the International Transducer Corporation feels that it accurately represents the receive response of the two that were used (Fig. A3).

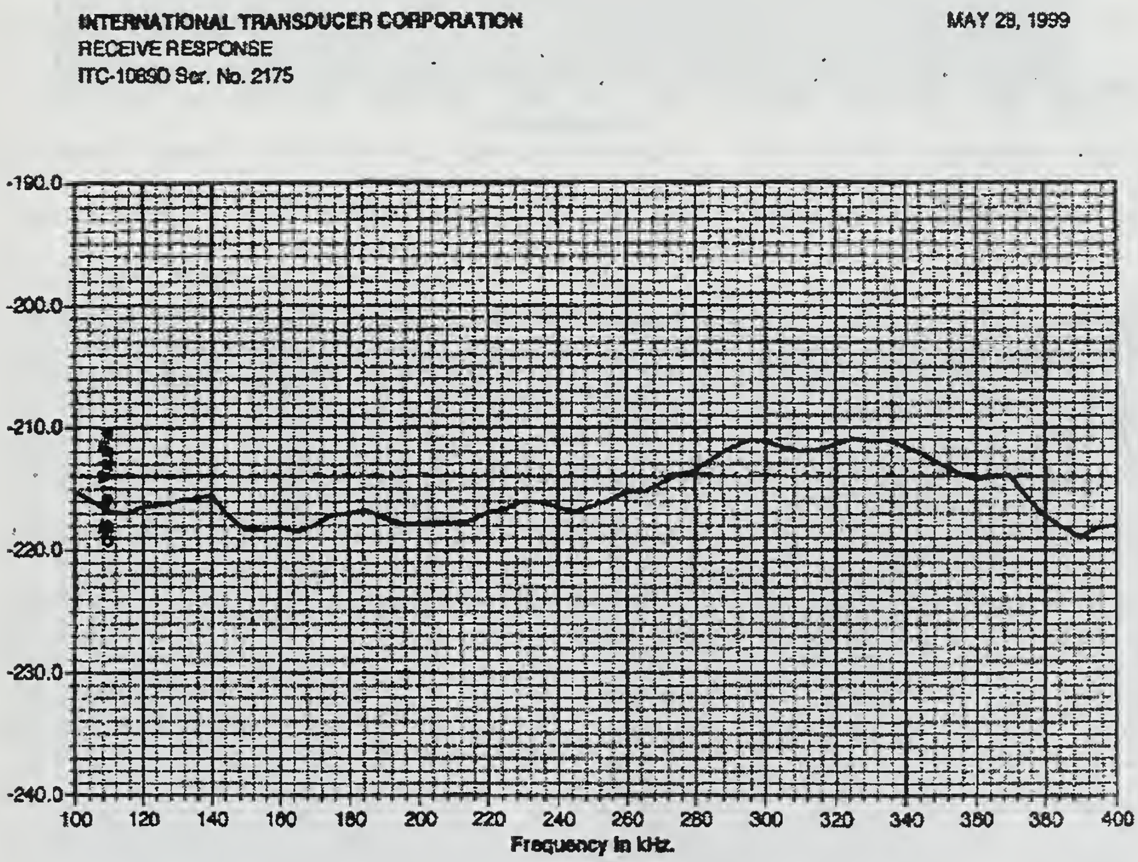


**Figure A1**. Receive Response for Transducer 2175

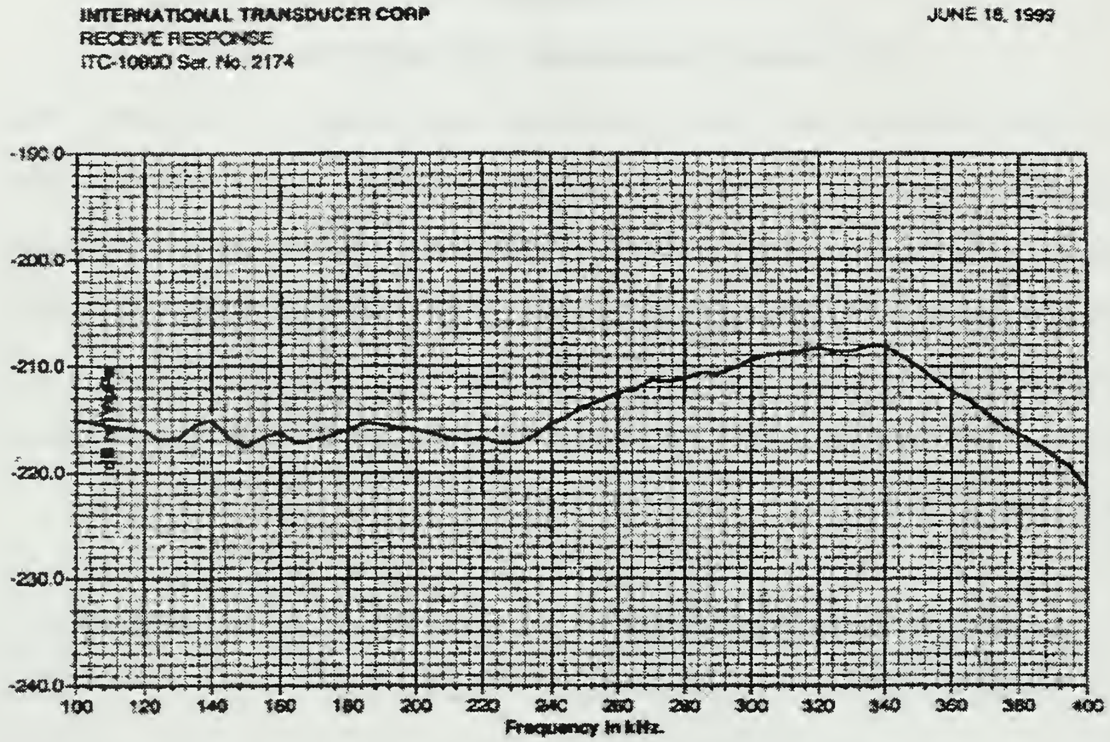


**Figure A2.** Receive Response for Transducer 2174

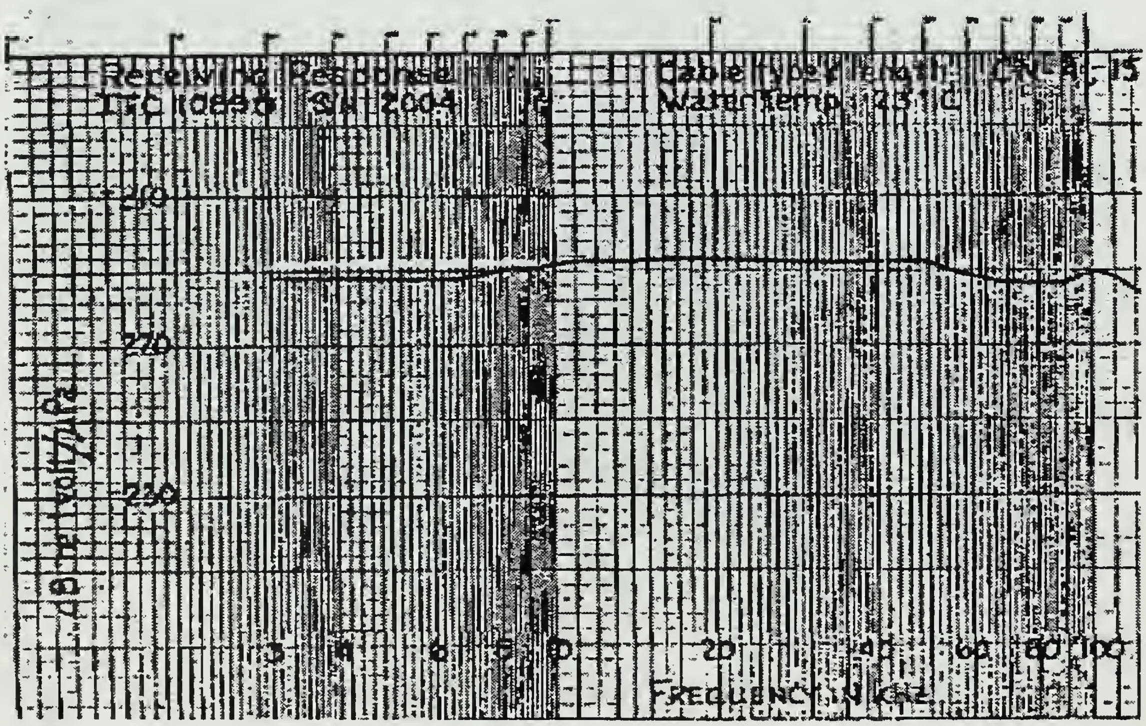


**Figure A3.** Generic Low Frequency Receive Response for ITC-1089D Transducers

## APPENDIX B

## FFT ALGORITHMS

In order to gain a greater understanding of the Dolphins sonar, MATLAB was used to analyze the Dolphin signals by performed FFT's on selected portions of the data. Several different scenarios were used to obtain the most accurate results. The MATLAB FFT program uses a fast radix-2 algorithm if the array or matrix being processed is a power of two. If not, it uses a much slower "non-power-of-two" algorithm. To speed processing, a power of two reference length was set within the FFT program, slightly higher than the actual data length. The FFT program then "zero pads" the data, meaning it adds zeroes to the end of the data before processing.

Since data in this experiment was sampled at 1MHz (1 million samples per second) the maximum signal frequency that could be recorded was 500kHz, according to the Nyquist Theorem. A waveform must be sampled at least twice per cycle to prevent aliasing, or the FFT program believing that the sampled waveform is a lower frequency than actual. It was initially believed that the zero padding would not significantly affect the accuracy of the data, following processing. However, several correlation trials were performed between data processed with zero padding and data processed without. Surprisingly, correlation coefficients ranged from 0.65 to 0.75, where 1.0 is perfectly correlated.

It could be said that the data processed with zero padding was only 65-75% accurate, since the data without zero padding had no extra signal introduced. The following figures demonstrate the difference between zero padded and non-zero padded data after FFT processing. Figure 8 shows a better view of a single click

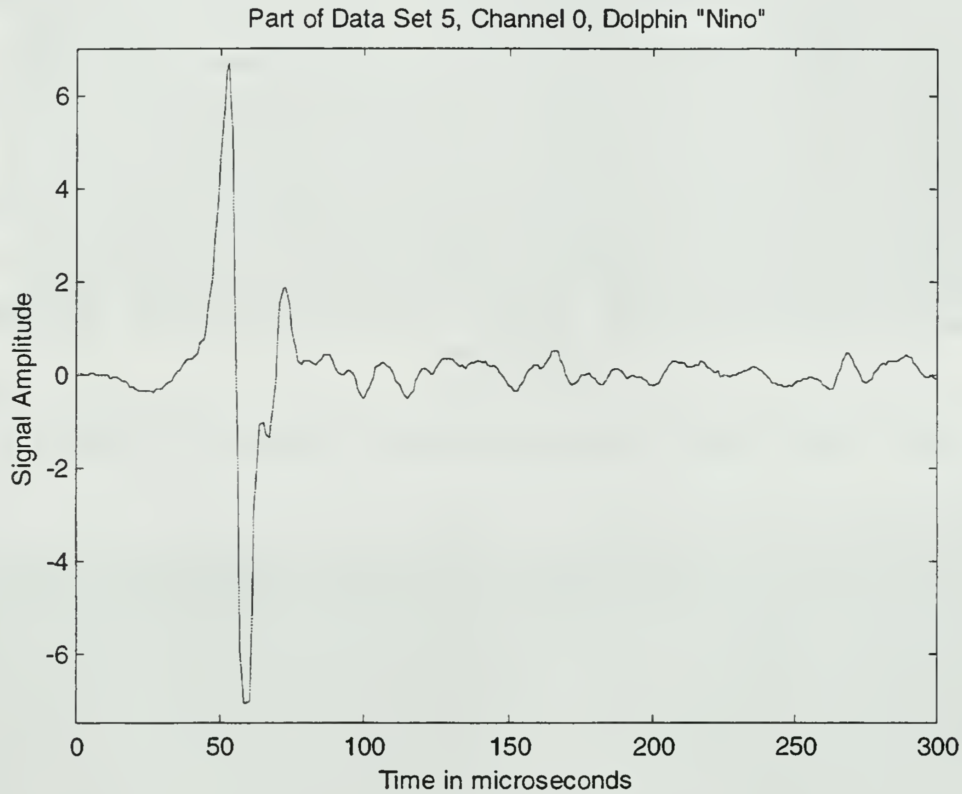


**Figure A4.** Click Used to Test FFT Algorithims

Figure 9 illustrates a portion of the plot used to compute the difference in the two FFT methods. The correlation coefficient between the FFT methods was calculated to be 0.6350, which is poor (1.0 is perfect correlation.) A power-of-two algorithm must have a data set that is as long as a power of 2, 2…4…8…16…32…etc. If the

data set is less than the power of two length, the algorithm adds the remaining number of zeroes to equal a power of two. Since the reference length for zero padding must be a power of two and longer than half the original sampling frequency (1MHz) or 500000, 2^19 was selected (2^19 = 524288). Essentially, MATLAB added 24288 additional zeroes to the end of the data in order to process the FFT using the faster algorithm. Adding the additional zeroes to the data caused the error, and the plot of the two types of FFT algorithms can be found in figure 10.

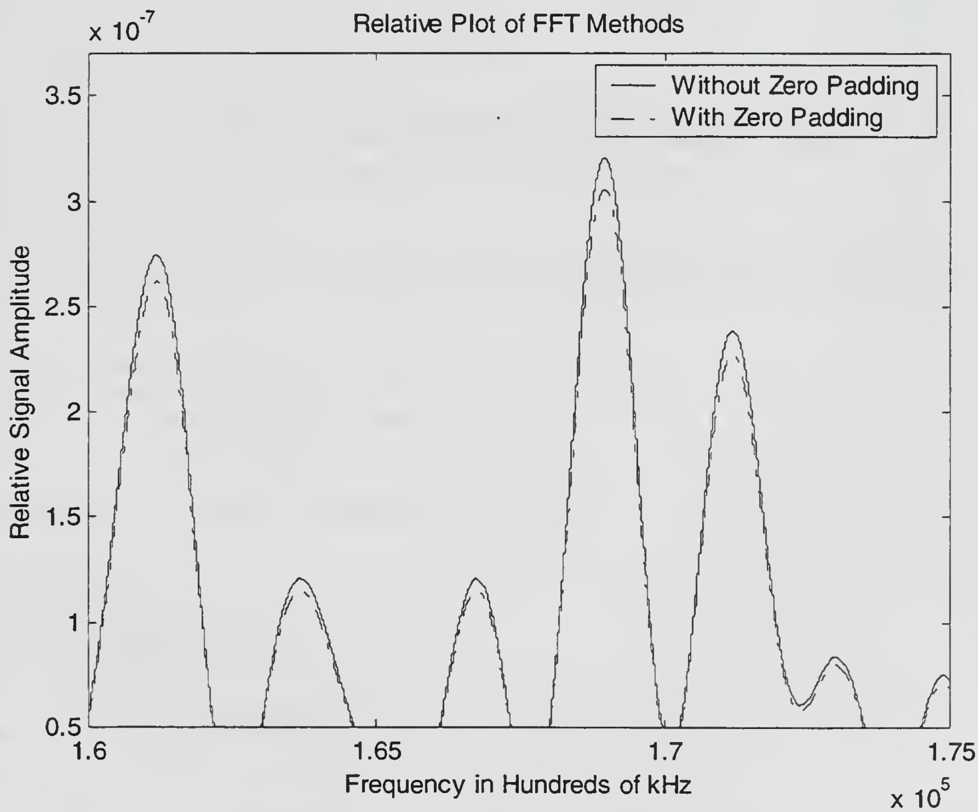


**Figure A5.** FFT Plot of a Single Click with Both Zero-padding and Non-zero-padding algorithims

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# APPENDIX C

## MATLAB CODE

### 1. Program to acquire sonar data.

```
%01 May 2000
%LT David Dye
%Naval Postgraduate School
%Dolphin sonar Project

clc
clear all

Fs = 1000000;
%Fs is Sample frequency in Hertz (cycles/second).
DataLength = 5000000;
%DataLength is the number of samples in data set DataLength/Fs = Data
%length in seconds.
ai = analoginput('nidaq',1);
%indicates acquisition device.
addchannel(ai,0);
%sets channel 0 as the first channel.
addchannel(ai,1);
%sets channel 1 as the second channel.
set(ai,'SampleRate',1000000);
%sets the sample rate by samples per second.
set(ai,'SamplesPerTrigger',5000000);
%sets the data length by number of total samples.
start(ai);
%begins data acquisition.
data = getdata(ai);
%sets variable "data" equal to all data acquired by the "getdata"
%function.
dataCh0 = data(:,1);
%creates a new variable for channel 0.
dataCh1 = data(:,2);
%creates a new variable for channel 1.
```

### 2. Program to load data and run FFT.

```
%17 Aug 2000
%LT David Dye
%Naval Postgraduate School
%Dolphin sonar Project

load ('D:\Dolphin Experiment\data0click19.mat');
%loads the indicated data set.

fMax = 500000;
%sets power of two limit for FFT.
%fMax could easily be changed to a "power-of-two" to utilize the fast
%Radix-2 algorithim for faster computation, but with introduced error.
fft1 = fft(data0click19,fMax);
%runs FFT on the data.
fft1der = fft1.*conj(fft1)/fMax;
%element by element multiplication with its conjugate converts complex
%data to real data.
f1 = 1000000*(0:((fMax/2)-1))/fMax;
```

```
%sets the variable to be used as the x-axis, frequency in Hertz.
figure(1);
%sets the figure number to be used.
semilogy(f1,fft1der(1:(fMax/2)));
%plots the relative magnitude, in log format, versus the frequency, in
%linear format.
```

APPENDIX D

DOLPHIN VIDEO STILL FRAMES

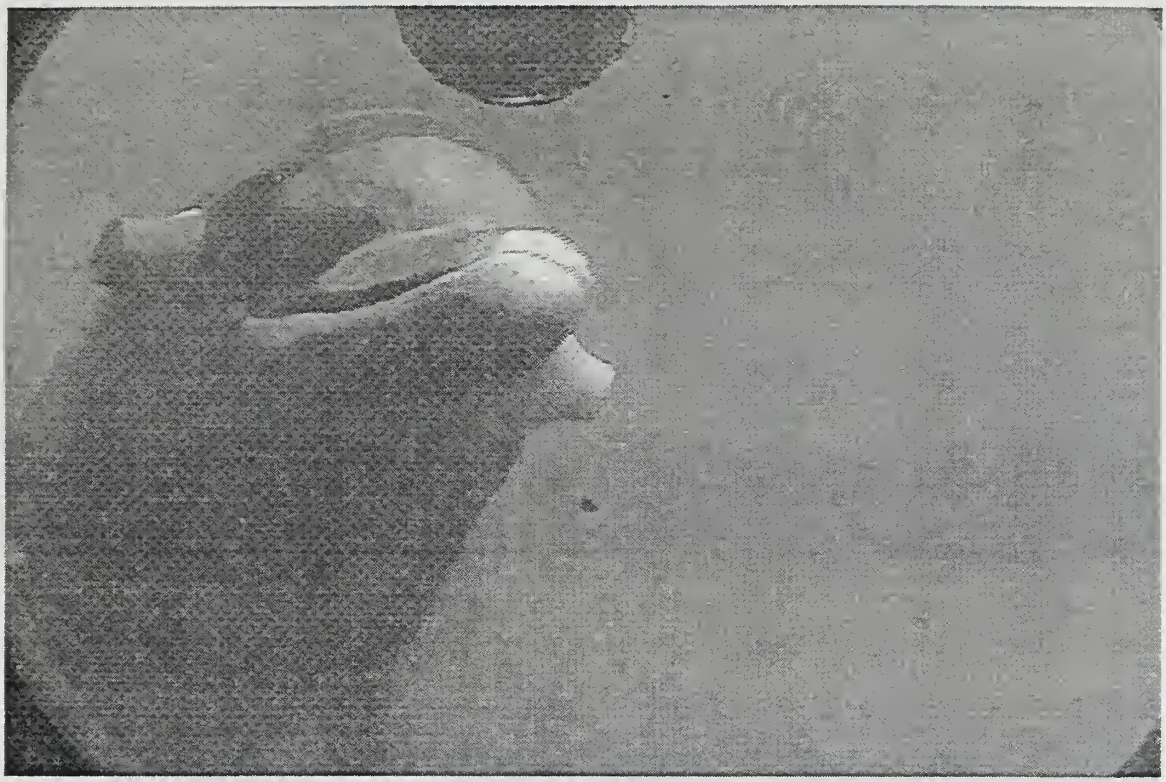

**Figure A6.** Dolphin "Buster" During Echolocation Task

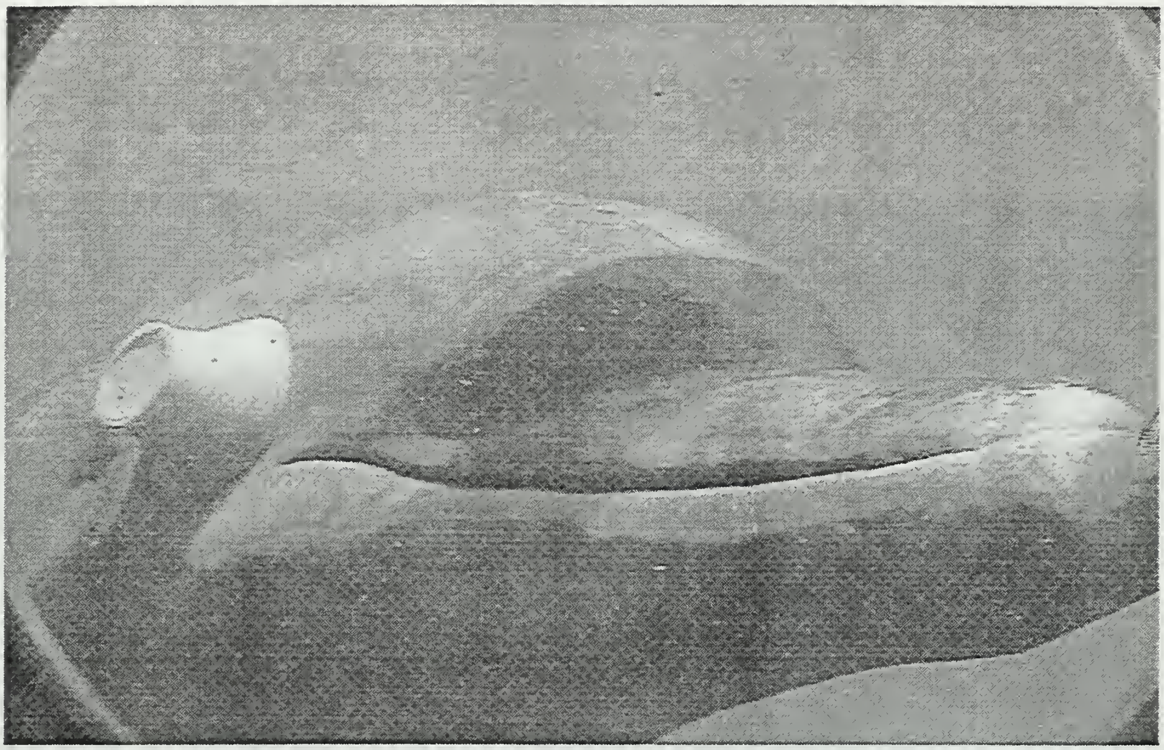

**Figure A7.** Dolphin "Nino" During Echolocation Task

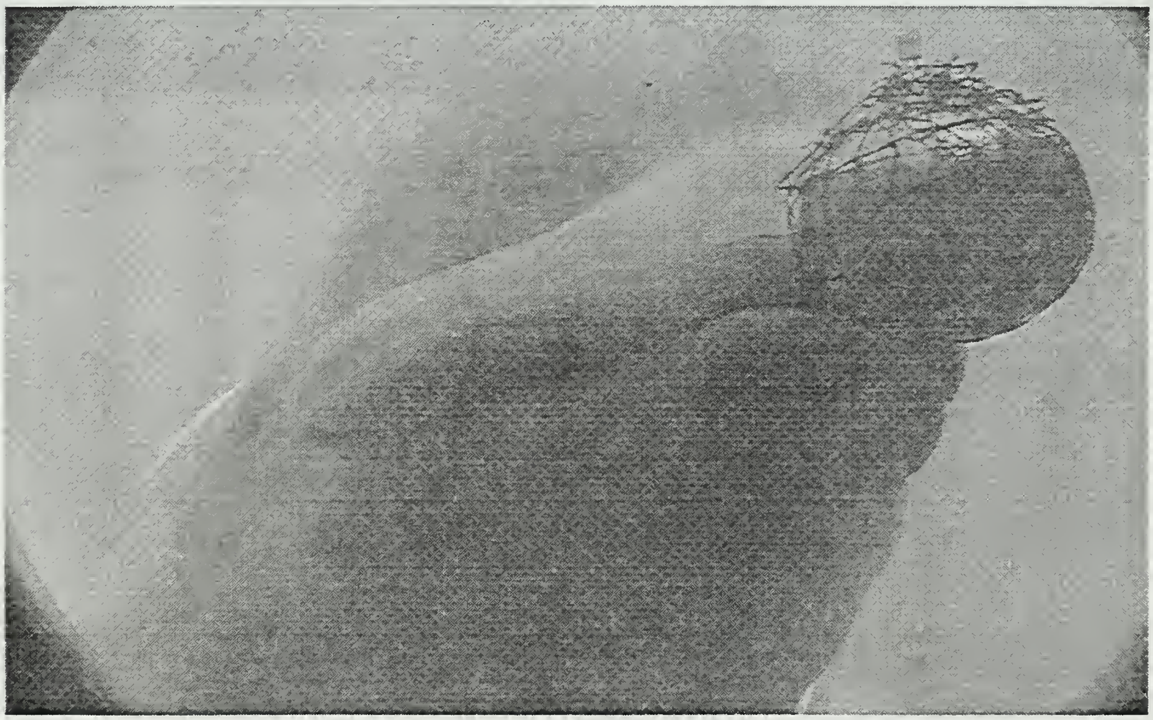

**Figure A8.** Beluga Whale "Muk-Tuk" During Echolocation Task

## LIST OF REFERENCES


1. Kaminga, C., Stuart, A., "Wave Shape Estimation of Delphinid Sonar Signals, A Parametric Model Approach," *Acoustic Letters*, Volume 19, Number 4, 1995.

2. Titov, A., *Investigation of Sonic Activity and Phenomenological Characteristics of The Echolocation Analyzer of Black Sea Delphinids*, Phd dissertation, Karadag, 1974.

3. Muir, T., *Role of Nonlinear Acoustics in Biosonar*, Proposal submitted to The Office of Naval Reaserch, 1997.

4. *United States Naval Mine Warfare Program*, Third Edition, Fiscal Year 1996-1997 Programs.

5. Renwick, D., Simmons, R., Truver, S., "Marine Mammals Are a Force Multiplier," *Proceedings*, Volume 123:8, pp. 52-55, 1997.

6. Ridgway, S., "Dolphin Hearing and Sound Production In Health and Illness," *Hearing and Other Senses: presentations in Honor of E.G. Weaver*, Amphora Press, Groton, 1983.

7. Brill, R., "The effects of attenuating returning echolocation signals at the lower jaw of a dolphin(*Tursiops truncatus*)," *The Journal of the Acoustical Society of America*, Volume 89, Number 6, 1991.

8. Kamminga, C., *Research on Dolphin Sounds*, Phd dissertation, Technical University of Delft, Delft Netherlands, 1996.

9. Evans, W., Diericks, J., Trochta, R., "Delphinid Sonar: Measurement and Analysis," *Journal of the Acoustical Society of America*, Volume 54:1, pp. 200-205, 1973.

10. Au, W., *The Sonar of Dolphins*, Springer-Verlag, New York, 1993.

11. Mitson, R., Morris, R., "Evidence of High Frequency Acoustic Emissions from the White Beaked Dolphin," *Journal of the Acoustical Society of America*, Volume 3:2, pp. 825-826, 1988.

12. Toland, R. *High Frequency Components in Bottlenose Dolphin Echolocation Signals,* Master's Thesis, Naval Postgraduate School, Monterey, CA, September 1998.

13. Ridgway, S., "An Illustration of Norris' Acostic Window," *Marine Mammal Science*, Volume 15, Number 4, pp. 926-930, 1999.

14. Ridgway, S., "Who Are the Whales?" *Bioacoustics, the International Journal of Animal Sound and its Recording*, Volume 8, pp. 3-20, AB Academic Publishers, 1997.

15. Ridgway, S., Carder, D., "Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin," *Journal of the Acoustic Society of America*, Volume 101, Number 1, pp. 590-594, 1997.

16. Kinsler, L., Frey, A., Coppins, A., Sanders, J. *Fundamentals of Acoustics*, Third Edition, John Wiley and Sons, 1982.

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